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Operation and Profitability of Batteries in Electricity Reserve Markets

In Espoo 29.5.2017
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Tiivistelmä

Globaalisti sähköntuotannossa on havaittavissa pyrkimystä vähentää kasvihuoneilmiötä lisäämällä sekä tuuli- että aurinkovoimaa. Näin ollen sähköntuotannossa esiintyy yhä enemmän tuotantoa, jota ei voida ohjata reaaliaikaisesti kulutuksen mukaisesti, mikä puolestaan kasvattaa verkon epävakautta. Tämän seurauksena ison mittakaavan sähkökemiallisia akkuvarastointijärjestelmiä pidetään potentiaalisena ratkaisuna sähköverkon tasapainotushaasteisiin.

1. Maaliskuuta 2017 aloitti Suomessa toimintansa 2 MW:n ja 1 MWh:n kokoinen litium-ioni akkuvarastointijärjestelmä nimeltään Batcave. Tämän diplomityön tarkoituksena on simuloida, miten kyseinen akkuvarastointijärjestelmä toimisi Suomen sähköreservi-markkinoilla vesivoiman avulla. Simulointi on suoritettu akkumallilla, joka on mallinnettu operoimaan taajuusohjatun käyttöreservin tuntimarkkinalla hyödyntäen vuoden 2016 tietoja. Akkusimulointiin valittiin kaksi skenaariota: All-skenaario ja Hydro-skenaario. All-skenaariossa akku toimii jokaisella mahdollisella tuottavalla markkina-tunnilla kun taas Hydro-skenaariossa akku toimii samoilla tunneilla kuin vesivoima.

Simulointitulokset osoittavat, että kaikista aktiivisista tunneista 8 % oli sellaista aikaa, jolloin akku ei pystynyt toimimaan, kun taas energiamäärällisesti se vastasi yli kolmasosaa energiavirtauksista, joita akku ei pystynyt toteuttamaan. Näin ollen ajallisesti akku pystyy operoimaan melko itsenäisesti, mutta jos tyhjäkäyntiä tapahtuu, niin vesivoimaa tarvitaan vastaamaan sen teknisiin vaatimuksiin. Tämän lisäksi ekstra-energiakapasiteetin hankkiminen olisi liian massiivista ja kallista, jotta täysin itsenäinen akkusysteemi voisi toimia ilman varareserviä tai ylimääräistä optimointia ja samalla pystyisi aina toteuttamaan pakolliset verkkovaatimukset.

Nettonykyarvolaskelmat akun elinajanodotteeseen asti osoittavat, että All-skenaariolla on paremmat tuotto-odotukset kuin Hydro-skenaariolla. Näin ollen on kannattavampaa käyttää akkua miltei niin paljon kuin mahdollista taatakseen nopea rahavirta kuin säästää sen käyttöä. All-skenaariolla projekti voi olla tuottava investointitukien kanssa. Lisäksi optimointilaskut viittaavat siihen, että akulla on havaittavissa tuottoisin tarjousväli taajuusohjatun käyttöreservin tuntimarkkinalla. Jatkotutkimukset on suotavaa kohdistaa akun systemaattiseen käyttöön ja aktiiviseen data-analysointiin, jotta akkumallia voitaisiin entisestään kehittää ja akkuvarastointisysteemin teknistä- ja taloudellista toimintaa parantaa.

Avainsanat Akku, akkuvarastointi, akkuvarastointisysteemi, sähköverkkovarastointi, akun käyttö, akun kannattavuus

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Abstract of master's thesis

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Abstract

A global trend in electricity generation has been that, in order to reduce the effect of global warming, wind and solar power will raise their share in the energy production. Consequently, there will be to more and more grid connected electricity generation that can't be designed in real time, depending on the required consumption needs, which increases the grid instability. Thus, large-scale electro-chemical battery storage systems have been considered as a potential solution for electricity imbalance challenges.

On March 1st 2017, a 2 MW and 1 MWh lithium ion battery energy storage system started operating in Finland under the project name of Batcave. The purpose of this thesis is to simulate how the battery storage system in question would operate in Finnish electricity reserve markets with the support of hydropower. The simulation is conducted with a designed battery model and operated throughout the data of 2016 in the hourly market of frequency containment reserve for normal operation. For the battery simulations two principal scenarios were chosen: All-scenario and Hydro-scenario. In All-scenario the battery operates in all possible market hours that provide income and in Hydro-scenario the battery functions in the same hours when the hydroelectric power would be operated.

Simulation results indicate that from all the active hours 8 % of that time the battery wasn't able to operate whereas it included over one third of the total energy flow that the battery wasn't capable of delivering. Thus, temporally the battery can operate alone rather well but when idling occurs, the hydro backup reserve is required to perform this task in a technical manner. Furthermore, the size and cost of additional energy capacities are too substantial in order to reach a completely autonomic battery with no backup reserves or additional optimizations and always carrying out the grid requirements.

From the net present value calculations throughout the battery life expectancy, All-scenario has better profitability prospects than Hydro-scenario. Consequently, it is more profitable to operate the battery almost as much as possible to assure quick cash flow than spare its use. With All-scenario the project can be profitable with an investment subsidy. The optimization calculations indicate that the minimum price limit of bidding the battery in frequency containment reserve for normal operation has a desirable scope of values. Further studies should focus on systematic battery use and active data analyzing to further improve the battery model and enhance the technical and economic operation of battery storage system.

Keywords Battery, battery storage, battery storage system, grid storage, battery operation, battery profitability

Foreword

This master's thesis has been written as an assignment for the Trading and Asset Optimization Unit in Fortum Oyj. On March 1st 2017 Fortum started operating a 2 MW and 1 MWh lithium ion battery energy storage system in Finland under the project name of Batcave. The purpose of this thesis is to simulate how the Batcave battery storage system would operate in Finnish electricity reserve markets with the support of hydropower. The new battery storage system offered a fresh and interesting subject to study and evaluate.

Above all, I would like to thank Fortum for providing me this grand possibility to do a master's thesis on a subject that has a great meaning for me. I would like to thank the head of Development-team, Tatu Kulla, for hiring me for this task and guiding me through this process. Before anything, I want to thank Roosa Nieminen as she has been the advisor for this thesis and helping significantly for its making. Additionally, I would like to acknowledge all the brilliant colleagues at Fortum that have assisted me during this project.

I would also like to express my gratitude to my thesis supervisor, professor Sanna Syri, for providing feedback on my thesis and encouraging me to continue on this intriguing subject.

Furthermore, I want to thank my parents for supporting me for all my life as well as my brother and sister for always backing me up. I would like to thank all my friends that I have been privileged to get to know along the way. Particularly, I want to acknowledge the following groups from University activities with no special order: Itmk12, Ftmk13, Kikh12, Kikh13, Kikh14 and the relating Vapaus. Before anything, from the bottom of my heart I want to thank my beloved girlfriend Jasmina for always standing by me.

In Espoo, 29.5.2017

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Nomenclature

°C	Celsius
C	C-rate
€	Euro
h	Hour
Hz	Hertz
kV	Kilovolt
m	Meter
MW	Megawatt
MWh	Megawatt-hour
TWh	Terawatt-hour
V	Volt
W	Watt

Acronyms

AC	Alternating current
BESS	Battery energy storage system
BMM	Battery management module
BMS	Battery management system
BSS	Battery storage system
CAPEX	Capital expenditures
CET	Central European Time
CO_2	Carbon dioxide
CSV	Comma-separated values
DC	Direct current
DOD	Depth of discharge
EOL	End-of-life
EPAD	Electricity Price Area Differentials
FCR	Frequency Containment Reserves
FCR-D	Frequency containment reserve for disturbances
FCR-N	Frequency containment reserve for normal operation
FRR	Frequency Restoration Reserves
FRR-A	Automatic frequency restoration reserve
FRR-M	Manual frequency restoration reserves
GRR	Grid Storage Solution
HVAC	Heating and air conditioning
MBMM	Master battery management module
NPV	Net present value
O&M	Operation and maintenance
OPEX	Operating expenses
PCS	Power conversion system
PV	Present value
RR	Replacement reserves
SOC	State of charge
SOH	State of health
SSC	System supervisory control
TEM	Finnish Ministry of Employment and the Economy
TSO	Transmission System Operators
UN	United Nations
VBA	Visual Basic for Applications
XFMR	Transformer

1 Introduction

The era of industrialization and the use of fossil fuels have led into significant release of carbon dioxide (CO_2) emissions and other greenhouse gases. The principal contributor to the human-induced climate change is the industrial electricity generation and other energy production that are conducted traditionally with combustion of fossil fuels, mainly with coal, oil and natural gas. (Höök & Tang, 2013)

The effects of climate change will have an huge impact on nature and consequently on people's health. Global warming will have its biggest effect on those nations that have the least admission to the world's resources and thus, the health of billions of people will be at risk. The impact of global warming will significantly increase as the temperature of the planet increases. Climate change will worsen floods, droughts, heatwaves and storms while the coastal cities are at the biggest risk for rising sea level. As the extreme climate events become more and more frequent as well as violent, together with reduced water and food security, the public health is increasingly at danger. Population growth, migrations and expanding diseases will only aggravate this problem. (Costello, et al., 2009) Consequently, the effects and consequences of climate change are too severe that they could be just ignored or understated.

After all, governments from all around the world have awoken to the rising problem of greenhouse effect from CO_2 emissions. The first framework convention of United Nations for general alignments against climate change came into effect in the year 1994. However, the first legally engaging agreement, known as the Kyoto Protocol, didn't take effect until the year 2005 which judicially obligated its member states to decrease carbon dioxide emissions. The most recent agreement to support the UN's convention on climate change was concluded on November 4th 2016 in Paris. This Paris Agreement has been ratified by 111 nations and it represents a share of 61 % from all the global emissions. The objective of the agreement in question is to keep the rise of the global average temperature under 1,5 °C in relation to the pre-industrial era with an absolute maximum increase of 2 °C. (Huttunen, 2017) Under the circumstances, countries from all around the world have an increasing interest to influence their predominant energy sources that maintain their power production and balances their electricity grids.

1.1 Global trend in electricity generation

In order to examine means to decrease the volume of carbon dioxide emissions, the current state of the global electricity generation has to be firstly studied and reviewed. In 2014 the world electricity generation represented approximately 23 816 TWh in which the fossil thermal fuels were dominating: 40,8 % with coal, 21,6 % with natural gas and 4,3 % with oil. In total, 66,7 % of the world electricity generation was powered by fossil fuels in 2014 and its triumphal march can be well observed in Figure 1 (IEA, 2016a).

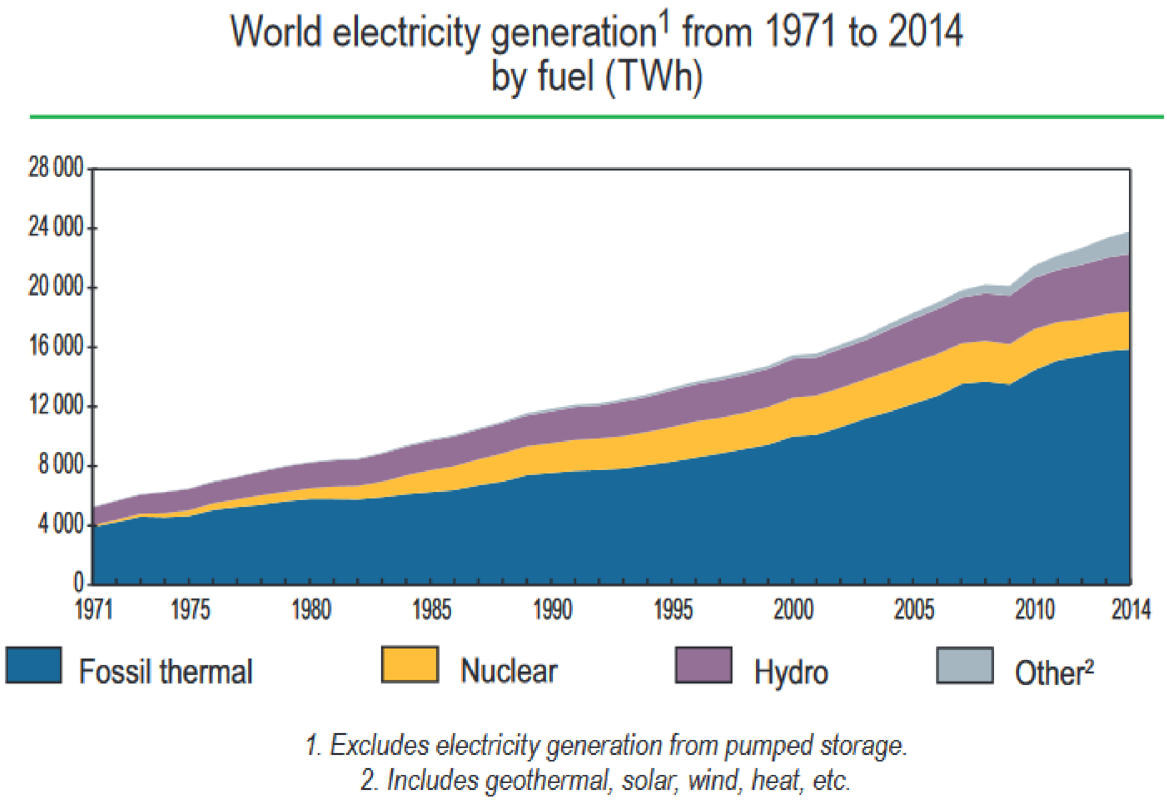


Figure 1: World electricity generation (IEA, 2016a).

Nevertheless, in 2014, when considering the world's total fuel combustion, coal, oil and natural gas produced together 32 381 Mt of the CO_2 emissions from which around 40 % was enforced in electricity generation. Additionally, because these used fossil fuels are identified as the main cause for mankind's high CO_2 emissions it has resulted in global interest to utilize more CO_2-neutral energy sources, generally referred as renewable energy sources. (IEA, 2016a)

In the year 2014 hydropower was the biggest representative of renewable energy sources in the world electricity generation with a share of 16,4 %, as seen from Figure 1. Besides that, geothermal, solar and wind stand for 4,2 % of the world electricity generation. (IEA, 2016b) Furthermore, these renewable energy sources grow at a considerable fast space: from 2013 to 2014 wind power increased with 11,1 % and solar PV technology with 35,1 % (IEA, 2016c). One significant reason for the increase in wind and solar power, beside their positive environmental effects and possibility for regional subsidies, is the decrease in their investment costs. In addition to the constant price progression, it has been estimated that between the years of 2020 and 2030 the investment cost of terrestrial wind power will decline with 12 % and PV solar power even with 37 % (Pöyry Group, 2016).

Consequently, as wind and solar power have highly volatile and uncertain energy production statuses, their rising share in the energy mix will result in searching for solutions to balance variations in electricity grid. When reviewing the basic function of a regional electricity grid, there has to be continuously the same amount of power production as there is consumption with end-customers. Historically, the balance has been acquired quite manageably as the fossil thermal plants could regulate their electricity generation depending on the wanted up-front production plans. If the production-consumption balance doesn't match accurately enough, then for instance hydropower could be used in those situations as reserve power.

As wind and solar power keep on increasing their share in the energy mix there will be more and more electricity generation that can't be planned in real time depending on the required consumption needs. On the contrary, electricity will be produced every time its windy or sun shines regardless of the actual need for it. Thus, there is a growing need for an economic intermediate energy storage between the volatile electricity generation and end-consumption. Traditionally hydropower has exercised this assignment efficiently but, as it's very challenging to build new damns, the volume of water power won't grow at the same pace in relation to the installed renewable energy sources. Apart from different proposed energy storage solutions of converting electricity, large-scale electrochemical battery storage systems have been considered as a potential solution for imbalance challenges.

In addition to difficulty in forecasting production and consumption, a rise in wind and solar power decreases overall grid system inertia which results in faster frequency changes (Tielens & Van Hertem, 2012). Inertia and the inertial response mean a natural stabilizing effect from conventional power plants that occurs when the frequency changes from the equilibrium state of the power system. The inertial response results from the kinetic energy that is caused by rotating masses of synchronous turbines and generators. The grid stabilizing generators absorb or inject electrical energy naturally into or from the grid to compensate the occurring frequency shifts. (Antic, et al., 2014) Nevertheless, as solar panels don't have rotating parts and wind turbines don't spin in sync with the grid frequency, issues can emerge when there is greatly renewable energy production and synchronous generators are shut down. However, with correct inverter control and with relatively small energy storage the grid inertia could be reproduced when needed. (Antic, et al., 2014) Thus, battery energy storage systems can improve the grid system stability and reduce the impact of wind power penetrations (Knap, et al., 2014).

During spring 2017 there were approximately 987 electro-chemical battery projects in the world which represent 3 134 MW of power capacity in various services or markets. From available battery technologies the lithium ion battery is the most dominant type representing, when compared to the other forms, 64 % from all installed number of pieces and 69 % of all installed power capacity. In Europe, there are 124 lithium-ion battery systems and they are concentrated mainly in Germany and in its surrounding areas. (DOE Global Energy Storage Database, 2017)

During April 2016 Fortum, a Finnish energy company, informed that it launches a 2 MW lithium ion battery energy storage project called "Batcave". It started operating in Finland on March 1st 2017 and it was recognized as the biggest battery storage system in the Nordic countries at that time. The large-scale battery in question was planned to operate in the Finnish electricity reserve markets where it could regulate the occasional grid imbalances. The object of this thesis is to have a closer study to the Batcave battery in question and investigate its operation possibilities in Finnish electricity markets.

1.2 Electricity generation in Finland

The usefulness of electrical batteries depends highly on the country's electricity generation infrastructure and allocation of different production forms. Consequently, in order to properly research the function and role of Batcave battery storage system in Finnish power markets the current and future trends in electricity generation have to be fully examined. First of all, in the year 2015 the volume of electricity consumption in Finland was 82,5 TWh. 80 % of this was produced in Finland and 20 % was imported from other Nordic countries, Russia or Estonia. (Statistics Finland, 2016)

From the total Finnish electricity generation a share of 45 % was enforced by renewable energy sources, mainly with hydropower and biofuels. Wind and solar power had a share of 3,5 % from the total electricity generation whereas nuclear had a 34 % share and fossil fuels 17 % share. When compared to the year 2014, the consumption of fossil fuels decreased with 23 % in electricity generation whereas the electricity volume produced by wind power was doubled. Although the share of fossil fuels in electricity generation varies between the years, it is noticeable that there is an overall decreasing trend with fossil fuels. (Statistics Finland, 2016) The evolution of energy source usages in Finnish electricity generation is demonstrated in Figure 2.

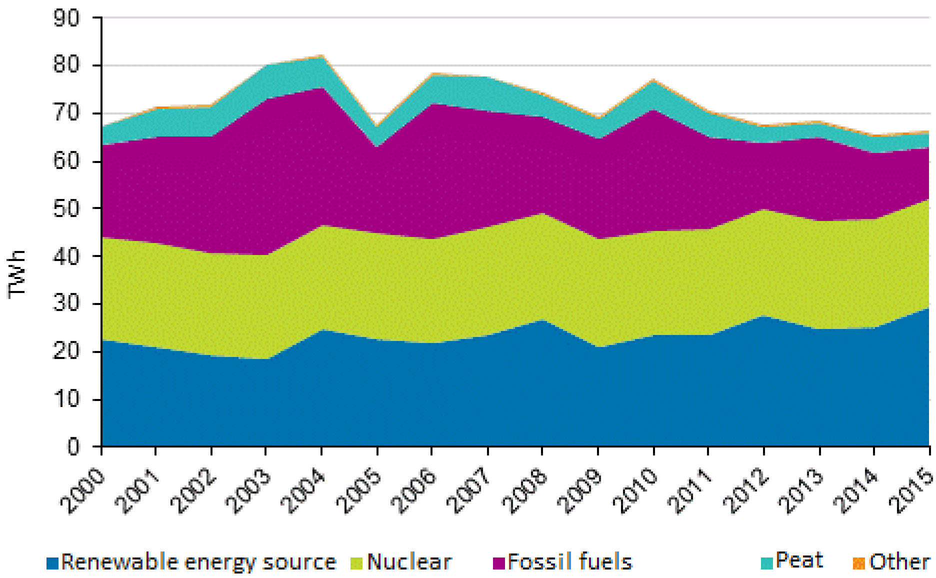


Figure 2: Finnish electricity generation by sources in 2000 - 2015 (Statistics Finland, 2016).

On November 24th 2016 the government of Finland accepted the national energy- and climate strategy for 2030 which is the most recent alignment to decrease local CO_2 emissions. In this strategy it is stated that by the end of the year 2030 Finland aims to have from the total energy end-consumption 50 % share with renewable energy, reach self-sufficiency with a share of 55 % and to stop using coal in energy production. The long-term goal is to reach a carbon-neutral society and possibly to have a completely renewable energy based nation by the year 2050. (Huttunen, 2017)

Part of the implementation of the Finnish Government Plan for Analysis, Assessment and Research for 2015 was to study the execution possibilities of the European Union 2030 energy policy and their impact on the energy production sector in Finland. The research in question also took into account the effects of implementing the goals of the national energy- and climate strategy that was presented in the earlier paragraph. During this study different modelling scenarios were used in order to simulate the impacts of climate policy until the end of year 2030. In Figure 3 the evolution of Finnish electricity generation is modelled according to the national requirements of energy policy and assuming a normal electricity generation growth rate. (Pöyry Group, 2016)

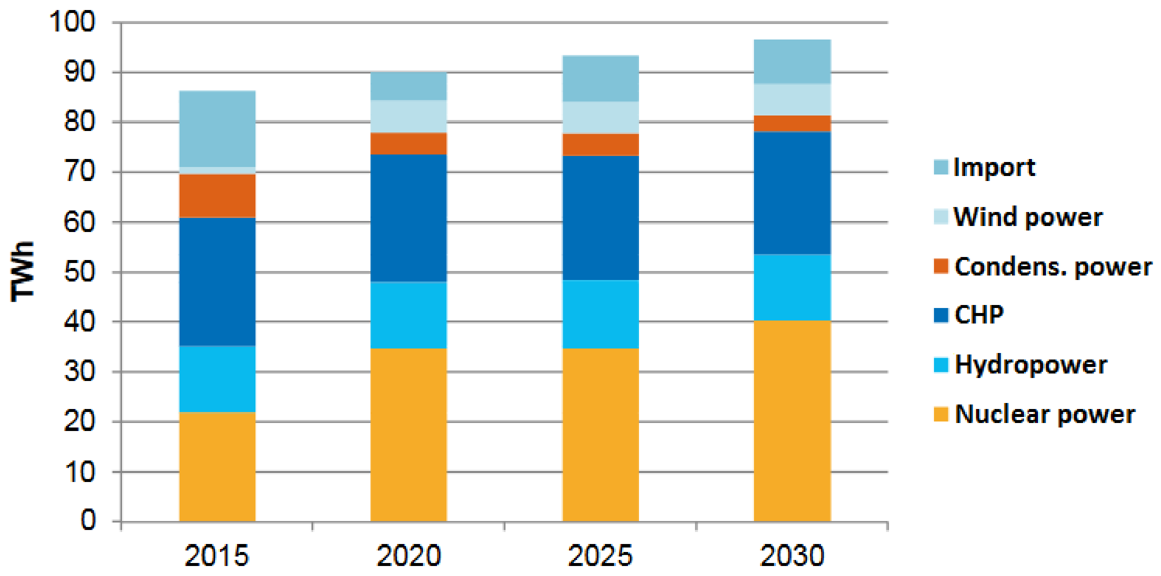


Figure 3: Finnish electricity generation modelling results according to the national requirements of energy policy and assuming a normal electricity generation rate (Pöyry Group, 2016).

As it can be stated from Figure 3 the increase in electricity generation stems primarily from increase in wind power, biofuels and nuclear energy. The growth of wind power is based solely on the Finnish subsidy system and after its ending it's presumable that wind power capacity won't increase significantly after 2020. The use of coal in CHP-plants will decrease and some part of it will be substituted with more expensive biofuels. (Pöyry Group, 2016) Consequently, because poorly flexible nuclear power will increase its share in the energy mix while simultaneously the share of adjustable fossil fuels will decrease, there is a potential need for economical grid balancing. Additionally, as there will occur considerable growth in volatile and uncertain wind power capacity rather soon, evaluation of a grid balancing battery storage system in Finnish electricity markets is worth researching. Consequently, the recently implemented Batcave battery storage system provides a suitable research and development project to study battery operations in Finland from a technical and economical viewpoint.

1.3 Structure of the thesis

The purpose of this thesis is to simulate how the Batcave battery storage system would operate in Finnish electricity reserve markets with the support of hydropower. This contains viewpoints about battery's technical characteristics and how they assist or constrain the operation possibilities. Additionally, the size of a stand-alone battery system is evaluated in order to get perspective about the influence of a hydro backup reserve. Moreover, the profitability prospects of Batcave are studied, and further, the outcomes help in reviewing the optimal practices to operate the battery storage system.

When it comes to energy storages, the scope of this thesis is kept solely on the electrochemical battery storage systems although other technologies for grid storing exist as well. This is because this study concentrates exclusively on simulating the Batcave battery storage system and thus that technology in question deserves a closer examination. The scope of this thesis would have grown excessively with all possible grid storage reviews and thus the other energy storages for grid-scale applications are excluded.

After this introduction the Chapter 2 starts with describing the current electricity market in Finland. In this chapter it is narrated how the power system works and how the different electricity market places function. The main three electricity market places in Finland are described while giving more attention to the Fingrid's reserve markets. This concentration on reserve markets is implemented because they are seen as the most suitable market place for battery technology which is explained in detail at the end of Chapter 2.

In Chapter 3 the concept of battery energy storage system is presented and explained. In this chapter different electrochemical battery types are reviewed and their characteristics are compared from a viewpoint of a battery storage system. Additionally, the battery management system, that secures an optimal procedure of each battery pack, is described alongside the other important battery storage system components. At the end of Chapter 3 the future role of battery storage systems is evaluated.

In Chapter 4 the Batcave battery storage system is demonstrated while concentrating on the following subjects: history of the project, technological features and data communication. Moreover, the battery life expectancy is explained at the end of this chapter as well as its influence on upcoming simulations.

In Chapter 5 the overall scope concentrates on explaining the conducted Batcave simulations. Firstly, the applied data is reviewed as well as its use in these simulations. Then, the actual simulation work is divided into two scenarios and their differences are listed in this chapter. Furthermore, the Batcave model, that is the heart of the simulations, is explained in detail as well as its reliability according to the real measurements acquired from the Batcave battery. Lastly, the presumptions and constraints of the simulations are presented at the end of Chapter 5.

In Chapter 6 the simulation results are presented and evaluated categorically. The outcomes will give answers for the thesis' research questions about the operation and profitability of Batcave battery. Consequently, battery's operational results are presented alongside the required sizes for virtual energy capacities. Furthermore, the profitability of scenarios shows the productivity possibilities of the Batcave project and ultimately the outcomes are utilized to calculate the optimal operation practices. At the end of Chapter 6 the conducted simulation results are evaluated and assessed. The final conclusions are drawn in Chapter 7.

2 Electricity market of Finland

The purpose of this thesis is to study how the Batcave battery storage system would operate in Finnish electricity reserve markets. In order to examine this theme in detail the whole electricity market of Finland has to be at first fully understood. An electric power system is the keystone of electricity markets and it covers energy production, the main grid, high-voltage distribution networks, distribution networks as well as electricity consumers. The power system of Finland belongs to the synchronous Nordic power system which involves also the areal systems of Sweden, Norway and eastern Denmark (Fingrid, 2016a). Moreover, the Nordic regional group in question has several interconnections with other countries. Western Denmark, Jutland, has a group of direct current (DC) connections from both Sweden and Norway and additionally Sweden has DC transmission connections to Germany, Poland and Lithuania. Furthermore, Norway has a DC connection to Netherlands and Finland is also linked to Russia and Estonia. (Fingrid, 2016b) The position of the Nordic regional group in the European electric System Operations Committee is demonstrated in Figure 4.

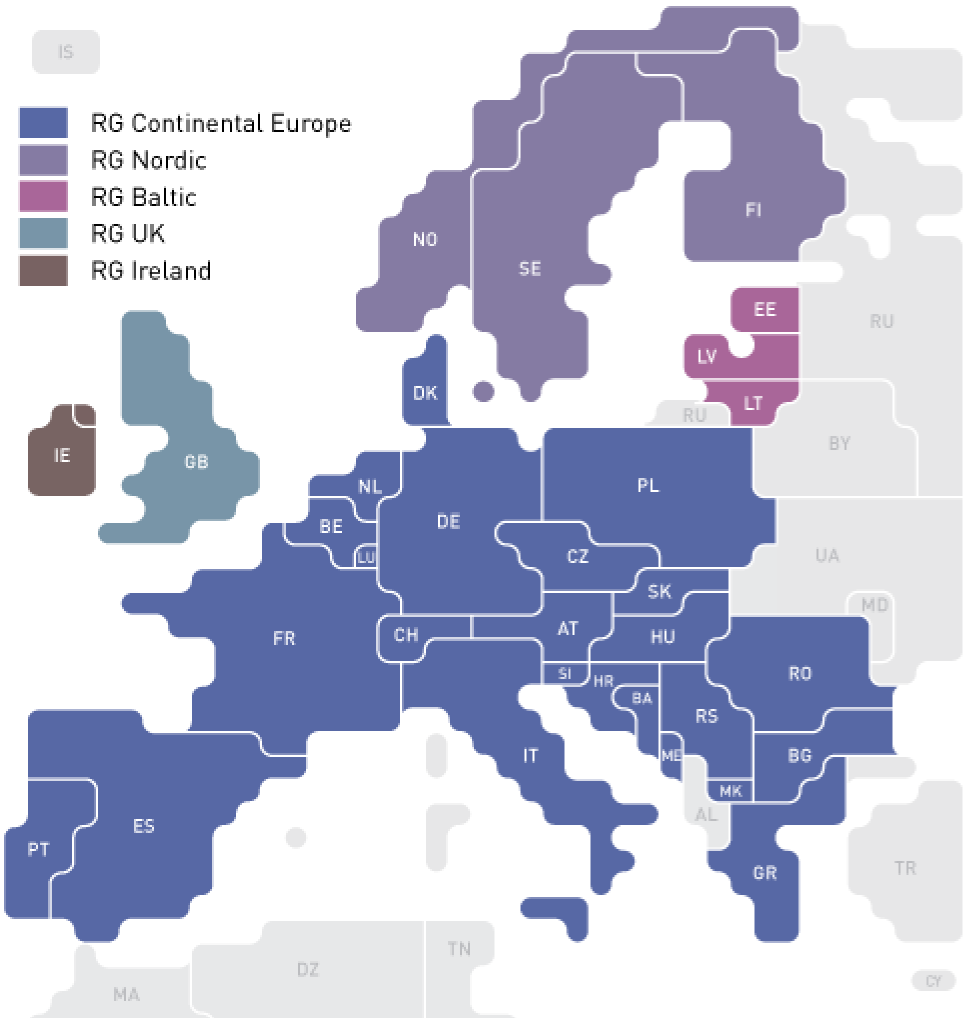


Figure 4: Regional groups of the European electric System Operations Committee (Entso-e, 2017).

2.1 Finnish power system

In the Nordic power system Fingrid Oyj is entrusted to operate the Finnish power system by the Finnish Energy Authority (Fingrid, 2016c). Consequently, the technical functionality and reliability of Finnish electricity grid belong to Fingrid's responsibility. Moreover, Fingrid has liability for nationwide balance operation management and imbalance settlement preparations in such a way that it's non-discriminative and equal for any party of the power market. This includes that the grid operator is, within its area of responsibility, in charge of maintaining the nominal frequency at 50 Hz, balancing of power supply and consumption, making an agreement of the balances and settling disturbances quickly. (Fingrid, 2016d) The power transmission network, that Fingrid is accountable for, is portrayed in Figure 5.

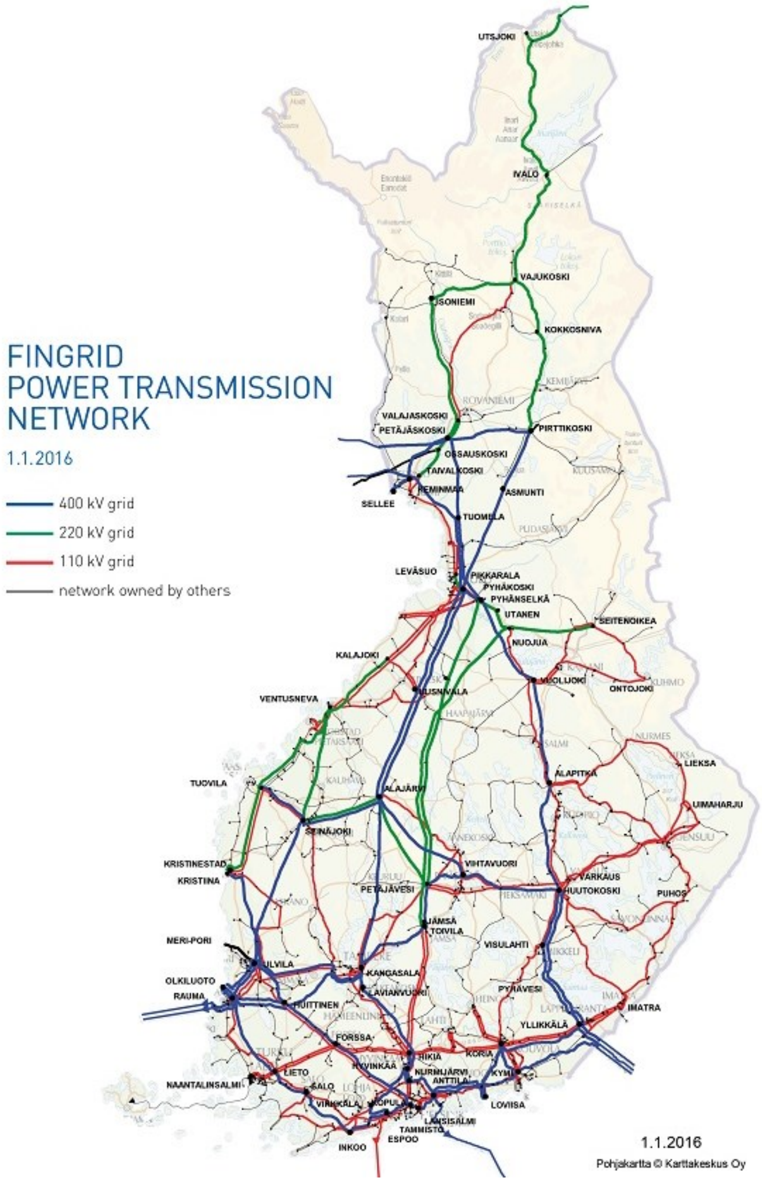


Figure 5: Fingrid power transmission network (Fingrid, 2016e).

2.2 Electricity market places

Before batteries can start operating in Finnish power system the most suitable electricity market has to be chosen for their balancing services. Universally, the entire Nordic power exchange is open and neutral market place where the electricity price is determined by rules of supply and demand. All the electricity products are standardized and the communication is designed to be fair for all the participants. The trading places of power exchange are divided into three categories: financial, physical and reserve markets. The listing in question is represented in a chronological manner in which the electricity trades are conducted. Figure 6 describes these Nordic electricity market places during different time intervals and with approximate volumes.

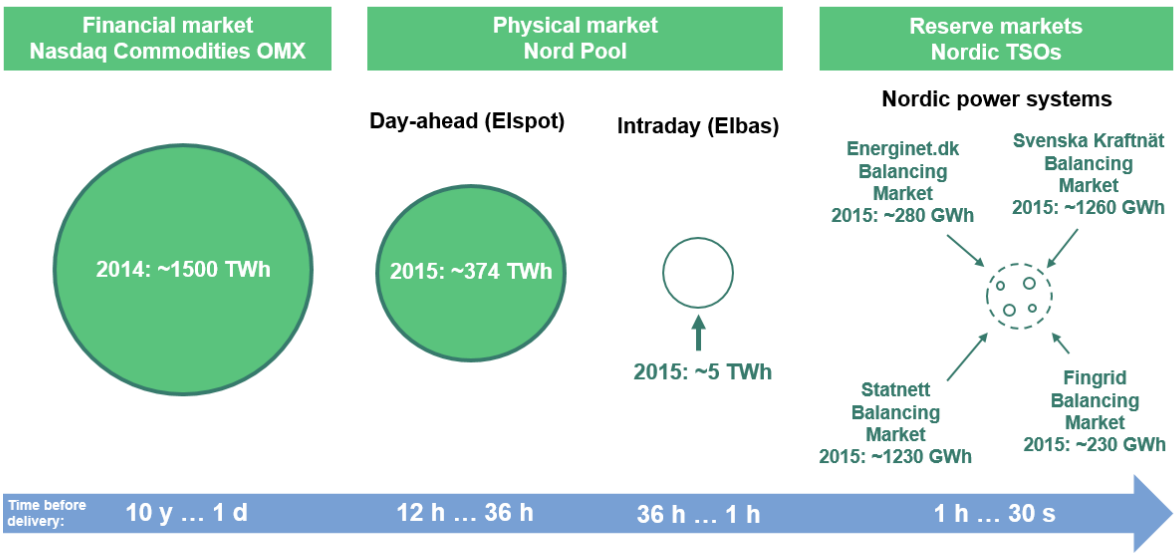


Figure 6: Nordic electricity market places. Data source: internal documents of Fortum.

2.2.1 Financial power markets

The derivatives trading in Nordic power markets is performed at Nasdaq OMX Commodities financial markets. There is no physical power delivery in financial markets and cash settlements are conducted throughout trading and delivery periods.

The derivatives market of financial trading floor is used for risk management and price hedging. With derivatives market it's possible to protect oneself from unfavorable price progressions by securing a required selling or buying price of electricity. The valuation of future electricity describes market expectations of the upcoming price level.

The financial contracts can have time intervals up to six years and the agreement period can be either day, week, month, quarter or a year. The Elspot system price from physical market of Nord Pool is applied as the reference price for the Nordic financial market. The Nasdaq OMX Commodities offer four different contract types depending on the risk assessments and time periods: Futures, Deferred Settlement Futures (DS Futures), Options and Electricity Price Area Differentials (EPAD). (Partanen, et al., 2014)

2.2.2 Physical power markets

Power trading in physical markets leads always to actual electricity delivery. In Nordic physical markets the trading is performed at Nord Pool which is owned by the Nordic transmission system operators portrayed in Figure 4. There are two trading mechanisms in Nord Pool, day-ahead market of Elspot and intraday market of Elbas. (Partanen, et al., 2014)

In these two Nord Pool markets the activation demands, prices and technical requirements for producers alternate according to their main objectives (Fingrid, 2016f).

2.2.2.1 Day-ahead market, Elspot

The day-ahead market in Nord Pool is the main forum for trading electricity as seen in Figure 6. The agreements are made between buyer and seller for the following day's power delivery.

A consumer, traditionally a utility, evaluates its energy need for the following day, hour by hour, and also calculates its price level for this amount. Meanwhile, a producer decides its deliver capacity and cost rate, hour by hour. These buying and selling offers are entered into the day-ahead market of Nord Pool. (Nord Pool, 2016a) Each order includes the exact electricity volume (MWh/h) at a specific price rate (€/MWh) for every hour in the next day that one is prepared to buy or sell (Nord Pool, 2016b).

The last time limit for submitting bids of the next day power delivery is set at 12.00 Central European Time (CET). According to the law of supply and demand the price equilibrium settles where the curves of supply and demand intersect which is demonstrated in Figure 7. Consequently, the balanced hourly prices are informed at 12.42 CET or later to the market. According to the agreed contracts, the hour for hour electricity volume deals are physically delivered the next day from 00.00 CET and until 24 hours onwards. (Nord Pool, 2016a)

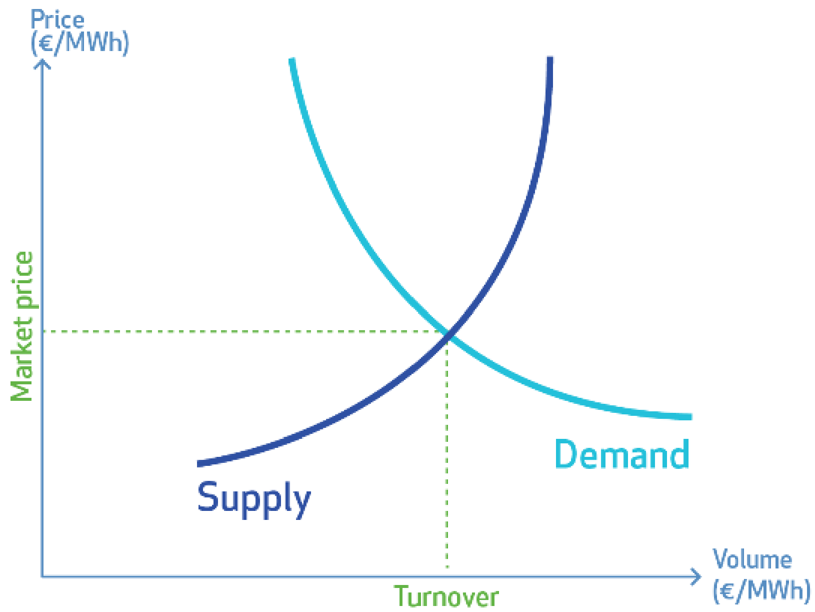


Figure 7: The supply and demand of day-ahead market (Fingrid, 2016a).

The balanced price is formed based on the following aspects. The buyer estimates at what price level he is prepared to pay the final kWh that would satisfy its demand. Alternatively, the selling price represents the cost level of producing the final kWh from the most expensive energy source in order to get system balanced. (Nord Pool, 2016b)

Beside the key factors of supply and demand, the transmission capacity presents also a considerable effect on the hourly market prices. If large energy amounts are required to be transmitted in case of demand needs it is possible that bottlenecks occur in those linked connections. To prevent these blockages the price is elevated in order to reduce the demand in the influenced areas. (Nord Pool, 2016a)

2.2.2.2 Intraday market, Elbas

The most of the energy volume that is covered by Nord Pool is dealt in the day-ahead market. Nevertheless, between the closing time of day-ahead market 12.00 CET and the next day delivery 00.00 CET there can occur unplanned incidents with power supply. For example, strong winds can suddenly accelerate power generation with wind turbines or a giant power plant may stop operating due to technical problems. The function of the intraday market in Nord Pool is to complement the day-ahead market and to secure the balance between supply and demand in the Nordic power market. The intraday market enables that the consumers and producers can trade electricity volume closer to real time.

The Nord Pool's available capacities for intraday markets are published every day at 14.00 CET. It's a constant market where the trades are made until one hour before the delivery. In intraday markets the best prices are accepted which comprehends both the highest buying price and the lowest selling cost.

Because of the increasing share of volatile wind and solar power in the forthcoming energy mix the intraday market is becoming increasingly significant. The power markets have a major role in development of near real time trades since the day-ahead agreements become more and more unpredictable. (Nord Pool, 2016c)

2.2.3 Fingrid's reserve markets

When it comes to the entire power system, the principal electricity exchange is operated in physical markets as seen in Figure 6. However, because the grid frequency has to be kept at all times at 50 Hz, or in its approximation, the physical markets alone can't regulate the occurring balance alterations sufficiently. Thus, reserve markets are designed to balance all the micro-shifts that appear in grid system due to the production and consumption variations.

According to System Operation Agreement made by the joint Nordic power system the TSOs of each country are obligated to maintain and balance their reserves. In Finland Fingrid has the mandate to operate as the transmission system operator. (Fingrid, 2016g) The Fingrid's reserve obligations and their sizes are listed in Table 1.

Table 1: Reserve obligations for Fingrid (Fingrid, 2016g).

Reserve product	Obligation
Frequency Containment Reserve for Normal operation (FCR-N)	~ 140 MW
Frequency Containment Reserve for Disturbances (FCR-D)	220 - 265 MW
Automatic Frequency Restoration Reserve (FRR-A)	70 MW
Fast Disturbance Reserve (FRR-M)	880 - 1100 MW

According to their main purposes the reserves are separated into three basic groups. The Frequency Containment Reserves (FCR) are activated automatically in a short time and they are used for the constant control of frequency. The Frequency Restoration Reserves (FRR) operate in a longer time interval and their function is to restore the frequency to its normal range. This enables that the activated FCRs can be released back to a state of readiness. Additionally, the purpose of Replacement Reserves (RR) is to release the activated FRRs back into use in the event of new disturbances. However, the Replacement Reserves are not applied in the Nordic power system and consequently they are not being observed in this thesis. (Fingrid, 2016h) The grouping of Finnish reserve products is presented in Figure 8.

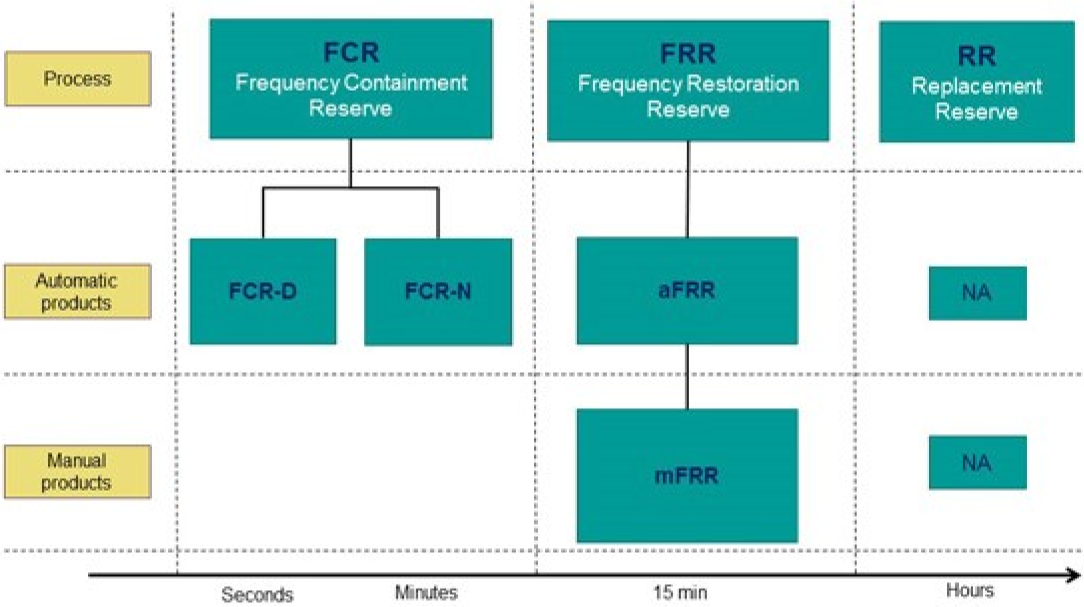


Figure 8: Reserve products in Finland (Fingrid, 2016h).

In more detail, the group of FRR consists of balancing power market (FRR-M), fast disturbance reserves (FRR-M) and automatic frequency restoration reserves (FRR-A). Furthermore, the group of Frequency Containment Reserves contain the market places of frequency containment reserve for normal operation (FCR-N) and the frequency containment reserve for disturbances (FCR-D). Briefly, in FRR the reserves can take longer time before activating themselves whereas in the FCR the starting times of reserves are far shorter. This chronological classification of reserve activation times is presented in Figure 9 in case of a grid frequency drop.

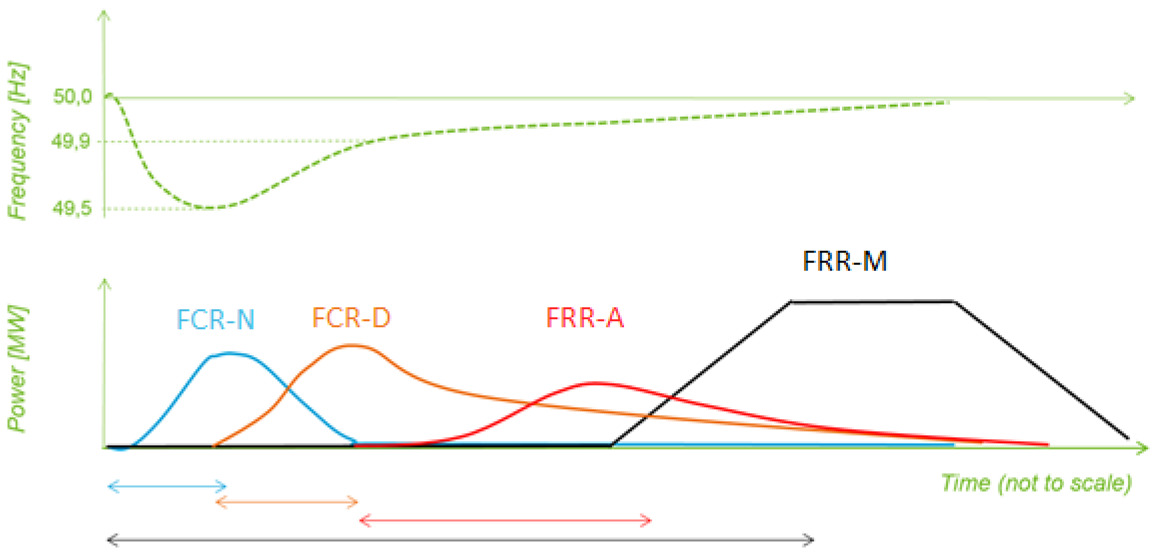


Figure 9: The activation order of reserves (Fortum, 2014).

Furthermore, the reserve market places have also alternative international names that Figure 9 represents logically: the FCR-N and FCR-D are also known as primary regulations, FRR-A as secondary regulation and finally FRR-M as tertiary regulation. These reserve markets are introduced in more detail in the forthcoming chapters.

2.2.3.1 Balancing power market, FRR-M

In the balancing power markets a balance service agreement enables that the energy producers can bid for their adjustable electrical energy capacity. This sets the balancing power market which enables frequency maintenance and grid balance management. As the activation of balancing power generation is operated manually the reserves are also called as the manual frequency restoration reserves (FRR-M or alternatively as mFRR).

The minimum requirements for the bids are that the power capacity can perform a 10 MW power change in 15 minutes. The balancing power bids have to be delivered to Fingrid at least 45 minutes before the starting of the delivered hour. The bid has to contain information about the capacity's power (MW), volume price level (€/MWh), transmission location and type of energy production.

From all the offered balancing power bids a Nordic balancing power bid list is being executed. The bids are set in order of price and they are consumed in that order depending on the power system demands. When the upper balancing power bids are applied the cheapest ones are used first and respectively in case of lower balancing bids the most high-priced bids are consumed first. The general classification of upper and lower balancing power bids is demonstrated in Figure 10.

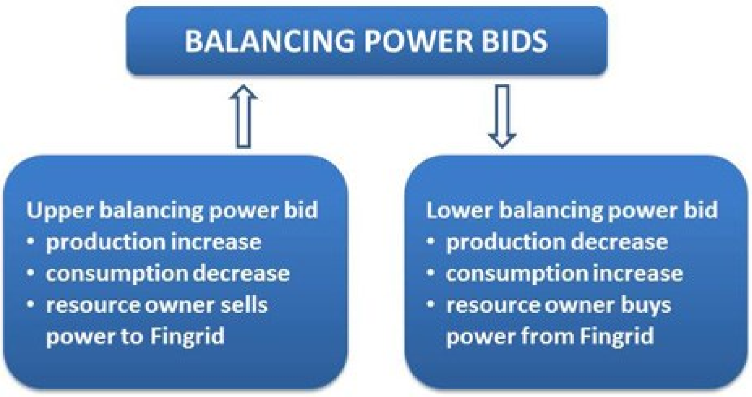


Figure 10: Balancing power bids (Fingrid, 2016i).

For each hour of use a price level of €/MWh is placed for both upper- and lower balancing power. All those energy producers from whom Fingrid has ordered upper- or lower balancing power will be compensated according to the agreed price level. (Fingrid, 2016i)

2.2.3.2 Fast disturbance reserve, FRR-M

In order to meet the Finnish reserve obligations Fingrid has ownership and long-term leasing contracts for different emergency power plants. These fast disturbance reserve power plants are not operational for commercial electricity production and the access right contracts are made with Fingrid for 10 years at least. (Fingrid, 2016j) The current fast disturbance reserves operating in Finland are portrayed in Figure 11. Because of the manual activation from Fingrid's Main Grid Control Centre, the reserves are also called as manual frequency restoration reserves (FRR-M or alternatively as mFRR) (Fingrid, 2016k).

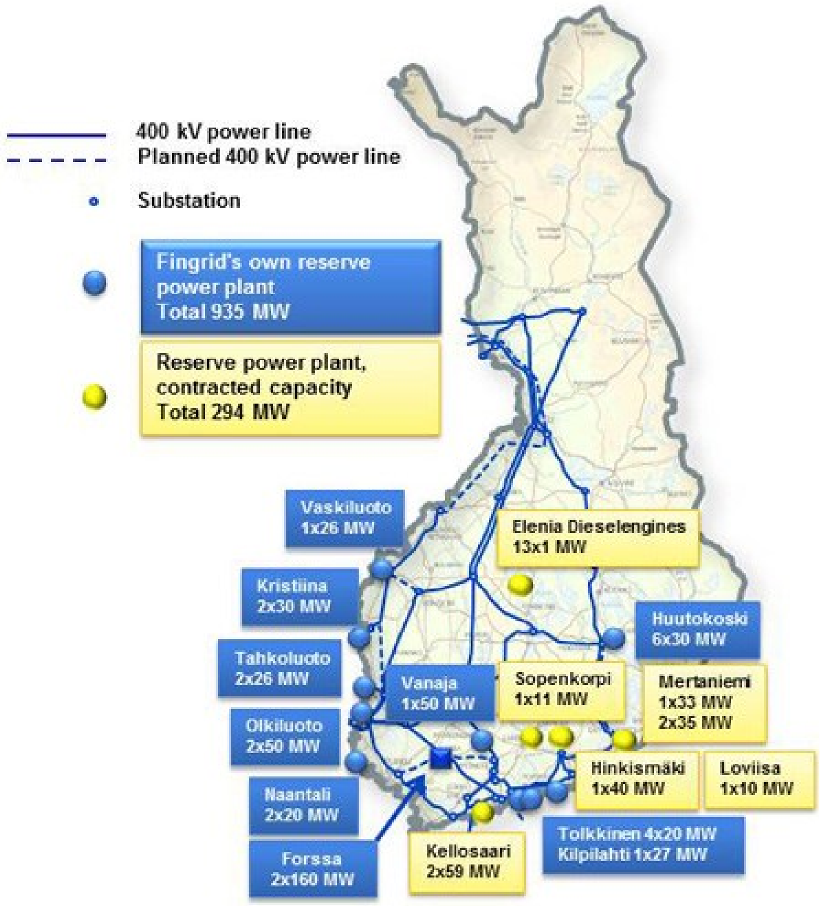


Figure 11: Fast disturbance reserves in Finland (Fingrid, 2016j).

Because the power plants of fast disturbance reserve markets are under Fingrid's control, and thus unable to enter any other market place, it doesn't leave other operative possibilities for the plant owners. Consequently, when considering power grid balance and reserve markets from the power producers point of view, the abbreviation of FRR-M is referred generally to the balancing power market whereas Fingrid more likely refers to its fast disturbance reserves with the abbreviation of FRR-M.

2.2.3.3 Automatic frequency restoration reserve, FRR-A

The automatic frequency restoration reserve market (FRR-A and also known as aFRR) was started by Fingrid in 2014. In FRR-A the bids are placed to the hourly market by producers for the upward and downward reserve capacities. (Fingrid, 2016l) During the year 2016 the hourly markets of FRR-A have generally been activated in the course of morning hours and again in the evening when there is the highest energy consumptions and frequency variation (Fingrid, 2016m).

The activation of automatic frequency restoration reserve depends on the frequency deviation of Nordic power system. The needed power transition is calculated from the frequency shifts in order to restore the grid frequency in its nominal value of 50 Hz and to discharge the activated Frequency Containment Reserves. Additionally, the target frequency can differ from the nominal frequency if its goal is to reset the time base of power system. The activation signal of power is send for the reserve holders from Fingrid every 10 seconds. If the needed activation demand is down adjustment the sign of the signal is negative and the other way round with the up upward adjustment. Fingrid sends the activation signals for the Finnish reserve holders according to the agreements from the hourly market.

Fingrid conveys two different types of activation signals, filtered and unfiltered, depending on the adjustment speed of the reserve. Typically the activation signal is filtered with hydropower because of its rapid operation speed. This enables that the 120 second maximal power activation time of FRR-A doesn't overlap accidently with other Frequency containment reserves. For unfiltered operation, such as power plants, the required activation time is lower as the production has already slower adjustment time. (Fingrid, 2016n)

2.2.3.4 Frequency Containment Reserves, FCR

The Frequency Containment Reserves include reserve units that are the first ones to balance appearing frequency shifts in grid system. Consequently, FCR is aimed to constantly control the nominal frequency of 50 Hz. In the Nordic power system two reserve functions are used: frequency containment reserve for normal operation (FCR-N) and frequency containment reserve for disturbances (FCR-D). The FCR-N is also known as frequency controlled normal operation reserve and the FCR-D as frequency controlled disturbance reserve.

The Frequency Containment Reserves operate as dynamic power reserves which activate automatically if the frequency changes. The function of FCR-N is to keep the frequency between values of 49,9 – 50,1 Hz. Additionally, if power generation gets unexpectedly disrupted, FCR-D substitutes the production deficits while keeping the frequency at least above 49,5 Hz. (Fingrid, 2016o)

Fingrid acquires the FCR-N and FCR-D from yearly and hourly markets, mainly from Finland but also from other Nordic countries as well as from Russia and Estonia. A Finnish reserve operator with accomplished prerequisites can offer its capacity for yearly or hourly market separately or alternatively for both together. The competitive bidding of yearly market for the next calendar year is organized in September or October. The yearly market excludes the possibility to participate during the middle of the yearly period. Nevertheless, it is possible to participate in the hourly market at any time during the calendar year. (Fingrid, 2016p) If reserve holder has signed a yearly market contract he can still take part in the hourly market as long as the yearly agreed volume is offered in full for that hour (Fingrid, 2016q).

The yearly and hourly markets share the same technical requirements and their principal market differences are listed in Table 2. The agreed frequency containment reserve contracts between Fingrid and other parties have identical terms of conditions, content and payments. (Fingrid, 2016r)

Table 2: The yearly and hourly market agreements for FCR-N and FCR-D (Fingrid, 2016r).

Yearly market	Hourly market
Bidding competition organized once a year (autumn).	A reserve owner can participate in the hourly market by making a separate agreement with Fingrid. This does not require making a yearly agreement.
In the middle of a contractual period, it is not possible to enter by making a yearly agreement for reserve maintenance.	Possible to enter the hourly market even in the middle of the year.
The amount based on reserve plans is bought in total.	TSO buys only required amount of reserve.
Reserve plans must be submitted the previous day by 6 pm.	Bids for the hours in the following 24-hour period must be submitted by 6.30 pm.
The operator is obliged to maintain the reserve it sells to the yearly market within the framework of its free capacity after Elspot market.	Reserve owners may submit daily offers for their reserve capacity. An operator that has a yearly agreement may participate in the hourly market only if it has supplied the reserve amount specified in the yearly agreement in full.
Fixed price is valid throughout the year. This is set based on the most expensive bid approved for the yearly market.	Payment is set based on the most expensive bid used separately for each hour.

When it comes to operation details, the unit of FCR-N shall regulate nearly linearly between the frequency range of 49,90 – 50,10 Hz in such a way that the dead band of frequency regulation operates between 50 $\pm$ 0,05 Hz at maximum. In case of frequency deviation of 0,10 Hz, the reserve shall be fully activated in three minutes. Unit operation in FCR-N market according to these minimum frequency requirements is demonstrated in Figure 12.

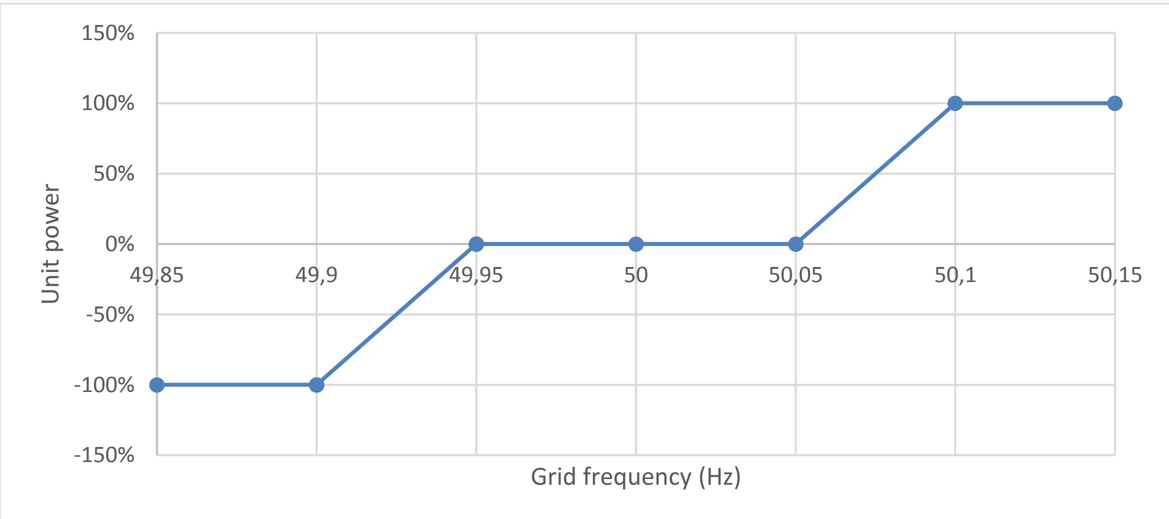


Figure 12: Operation of a reserve unit in FCR-N market according to minimum frequency requirements. Data source: (Fingrid, 2016p).

A power plant unit of FCR-D shall regulate nearly linearly in such a way that the activation starts when the frequency drops below 49,90 Hz and reach full activation at a frequency of

49,50 Hz. In five seconds half of the FCR-D shall be activated and in 30 seconds the whole reserve shall be activated with a stepped frequency change of -0,50 Hz. Operation of a reserve unit in FCR-D market according to these minimum frequency requirements is demonstrated in Figure 13.

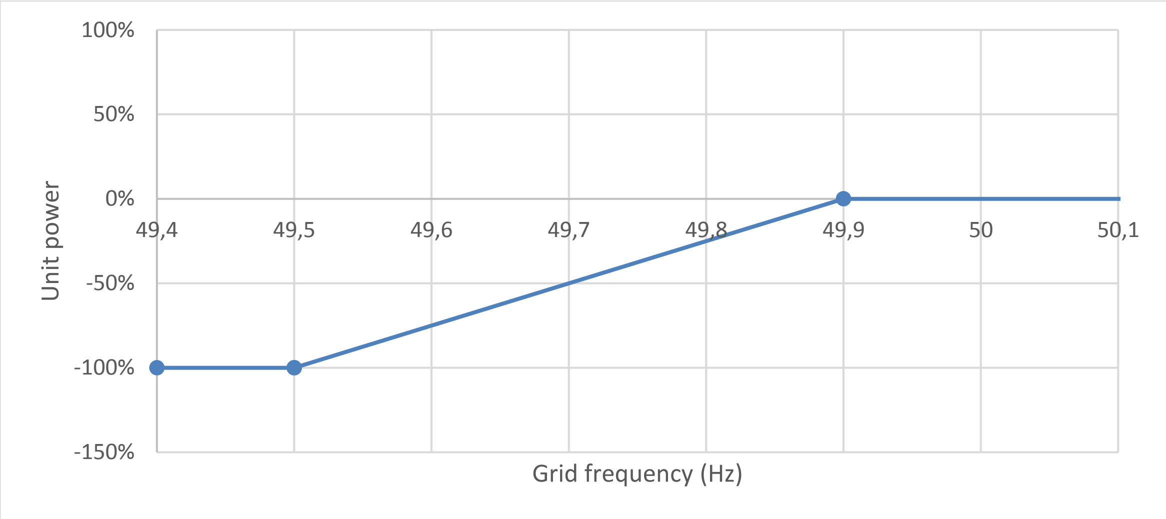


Figure 13: Operation of a reserve unit in FCR-D market according to minimum frequency requirements. Data source: (Fingrid, 2016p).

In case of relay-connected load of FCR-D the reserve shall disconnect itself in five seconds if the frequency is under 49,70 Hz or in one second if the frequency is under 49,50 Hz. The load can be reconnected to the grid by the reserve holder if the frequency has remained, at the very least, for three second at 49,90 Hz.

The TSOs of Nordic countries divide annually the obligation of FCR-N between power system areas relatively to the consumed energy proportion. For Finland the need for FCR-N is approximately 140 MW. Furthermore, the obligation of FCR-D is distributed weekly in relation to dimensioning faults. For Finland the obligation has been around 260 MW. (Fingrid, 2016p) Historical data about the FCR yearly and hourly market sizes and their price levels can be found in Chapter 2.3.2.

For FCR-N the minimum capacity of one bid is 0,1 MW and the maximum is 5 MW. Furthermore, for FCR-D the minimum capacity of one bid is 1 MW and the maximum is 10 MW. In the reserve markets the submitted accuracy is 0,1 MW and several bids can be proposed as long as they are processed separately without linkage to each other.

The bids of next calendar day in the hourly market have to be submitted before 18.30 o'clock. Then, Fingrid organizes the bids in a price sequence in order to give priority for the cheapest bids. Depending on the Fingrid's requirements a necessary amount of bids are accepted. (Fingrid, 2016q)

2.3 Battery operation in electricity markets

The benefit of electrochemical batteries is that they can react fast to the requirements of power grid and adapt efficiently to its variations. Moreover, batteries have good efficiency ratios as there is no mechanical movement required for preserving electrical energy, contrary to for example pumped hydroelectric energy storages. Nevertheless, batteries are expensive and their ability to store huge amounts of energy for longer time periods is fairly restricted. (Haisheng, et al., 2009) Thus, slow operation requirements and large-scale load leveling with low-priced electric energy (€/MWh) doesn't take into account the best characteristics of batteries. Consequently, electrochemical batteries don't normally thrive in physical power markets whereas they seem to have best profitability prospects in reserve markets. In addition to these, as financial power markets don't have any physical power delivery and cash settlements are conducted throughout long trading and delivery periods, the derivatives market place in question is naturally out of question for batteries.

2.3.1 Economic challenges of batteries in physical power markets

In physical power markets, where most of the actual electricity generation is concentrated, the price level is determined by the law of supply and demand. The competition with electricity energy volumes is severe which has kept the prices relatively low in Nord Pool area during recent years (Nord Pool, 2017).

The consumption order of energy sources depends on their production costs meaning that the cheapest forms of electricity generation are used first and then moved to more expensive ones until the energy need is fulfilled. A general display of Finnish price formation in electricity markets according to power sources is presented in Figure 14. However, it has to be noted that although hydropower has inexpensive variable production cost, as seen in Figure 14, it's not a primarily used energy source in physical markets because its operation is limited by the water volumes in reservoirs and rivers. Otherwise, in Figure 14 the order of energy sources is accurate to fulfill the national electricity need.

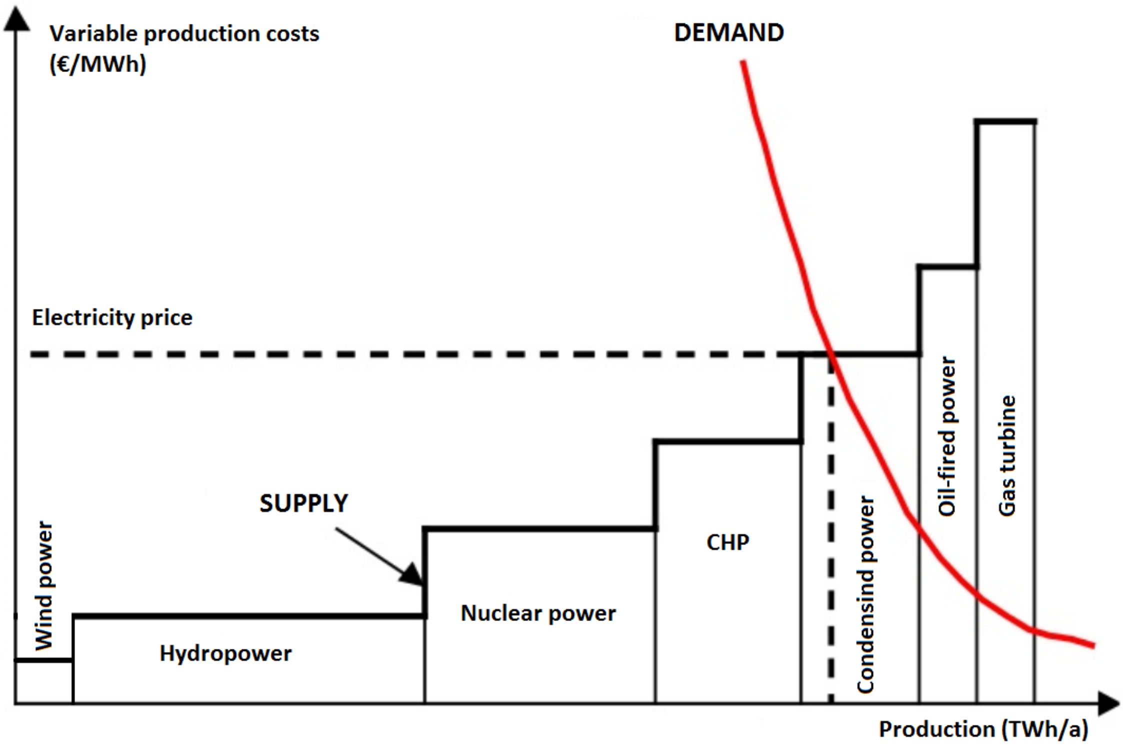


Figure 14: Finnish price formation in electricity markets according to energy supply and yearly demand. Data source: (Partanen, 2016).

Wind power, nuclear power and CHP-electricity are forming the basis of physical power markets where they are used as much as sensibly possibly. In a generic situation the extra condensing power determines the equilibrium price level which is yet relatively low in Nord Pool. (Partanen, 2016) Because the price volatility and trading arbitrage aren't sufficiently big enough in physical market, a battery system doesn't appear to be economically viable in charging with low price and discharging with higher price. Furthermore, combined with challenges to predict future price scenarios, expensive batteries doesn't seem to be profitable in physical markets at the moment. Moreover, as huge energy volume transmissions are normally required in this market, the limited size of energy capacities set clear restrictions for batteries to be functional enough. In order to underline the economic challenges for batteries, the Elspot hourly prices are portrayed in Appendix 1 from day-ahead market in Finland during the year 2016. From there it's observable that the price volatility has too small gap values in order to make energy trading arbitrage profitable with expensive batteries.

2.3.2 Battery suitability for reserve markets

Generally, it can be stated that the more demanding the operation requirements are, the less there are reserve units capable of realizing them. Consequently, the achieved monetary compensations are normally higher for a producer if those strict demands can be fulfilled. As battery technology enables short activation times, effective reactions for frequency variations and good efficiency ratios, batteries are well suited for the most demanding operations in the reserve markets (Haisheng, et al., 2009). Therefore, in electricity reserve markets the Frequency Containment Reserves (FCR), where the reserve units have to quickly adapt to frequency shifts, are considered as the most suitable electricity markets for battery functions. Thus, the Frequency Restoration Reserves (FRR) with balancing power market (FRR-M) and automatic frequency restoration reserve (FRR-A) don't offer as demanding requirements as the FCR market and therefore their lower price levels don't provide sufficiently good profitability prospects for battery operations.

In Finland, the absolutely biggest share in FCR-N and FCR-D markets is produced by hydropower. In hydropower water is guided to flow through a turbine which leads to generator turning and thus resulting in electricity generation (Fortum, 2017a). Hydropower has capabilities to generate relatively cheap power that doesn't have theoretically any marginal costs. However, the demanding operation requirements of FCR markets wear the gear parts of damn machinery effectively which results in expensive maintenance works (Fortum, 2017b). Thus, the use of batteries could compensate the use of hydro-electricity in robust FCR markets and make water power more available in other markets. In addition to the market size of hydropower, all the Finnish dams and reservoirs are rather built so there won't be high expectancies to have significantly more water capacity increase (Aslani, et al., 2013).

Furthermore, the use of hydropower is restricted by the water volumes in rivers and water levels in reservoir. Therefore, the annual capability of water power depends on the amount of rainfall and volume of snowmelt in Finland and in Nordic countries. The relation of reservoir water level and its monetary price is determined as a categorization of water value. Water value is defined as the "shadow price for water" in units of €/MWh. It means that when the water level in reservoir rises the water value decreases and the other way round when the water level in reservoir decreases. Consequently, water value signifies the price level at which a hydropower producer is willing to sell its water power. (Kervinen, 2010)

This has respectively an influence on the FCR-N and FCR-D markets and naturally on the profitability prospects of batteries as hydropower is dominating these markets.

The FCR markets are divided into yearly and hourly markets as classified in Table 2. The absolutely biggest share is traded in yearly markets as it guarantees certain portion of sales for producers which mitigates unwanted uncertainty factors. The FCR yearly market prices and sizes from the year 2011 to 2017 are presented in Table 3. To notice, during the year 2017 in FCR-D yearly market of capacity, there is a load of 41,5 MW that is activated with one step to which an acquisition limit of 100 MW is applied. This is marked with an (*) in Table 3.

Table 3: FCR yearly market prices and sizes in Finland (Fingrid, 2017c).

Year	FCR-N price (€/MW,h)	FCR-N capacity (MW)	FCR-D price (€/MW,h)	FCR-D capacity (MW)
2011	9,97	71	1,48	244,3
2012	11,97	72,7	2,8	346,9
2013	14,36	73,5	3,36	299,8
2014	15,8	75,4	4,03	318,7
2015	16,21	73,6	4,13	297,5
2016	17,42	89	4,5	367
2017	13,00	55,0	4,7	455,7*

In order to have a full picture about the possible FCR market places for battery operations, the historical data of FCR-D hourly market is represented in Table 4 and the historical data of FCR-N hourly market is represented in Table 5.

Table 4: FCR-D hourly market prices and sizes in Finland. Data source: (Fingrid, 2017d).

Year	Max price (€/MW)	Average price (€/MW)	Max capacity (MW)	Average capacity (MW)
2011	745,00	16,94	80	6
2012	480,00	6,02	46	2
2013	600,00	23,38	77	11
2014	420,00	7,98	74	6
2015	500,00	14,43	115	12
2016	150,00	5,15	73	5

Table 5: FCR-N hourly market prices and sizes in Finland. Data source: (Fingrid, 2017e).

Year	Max price (€/MW)	Average price (€/MW)	Max capacity (MW)	Average capacity (MW)
2011	770,00	14,94	58	2
2012	560,00	30,41	51	7
2013	514,00	36,33	64	10
2014	520,00	31,93	86	15
2015	500,00	22,32	75	14
2016	104,20	16,81	57	10

As it can evaluated from Table 3 and comparing statistics between Table 4 and Table 5, the FCR-N markets have better fixed prices as well as average prices than FCR-D markets. Thus, during every year between the data of 2011 - 2016 the FCR-N markets offer better profitability scenarios than FCR-D markets. This observation is in line with the previous statement that the more demanding the operation requirements are, the better profitability prospects can be expected. Consequently, FCR-N markets seem more suitable for battery operations than FCR-D markets which also supports the best aspects of batteries.

When comparing the FCR-N yearly and FCR-N hourly markets the average price in hourly market is clearly higher than the fixed value in the yearly market (expect for the year 2016). This means that, on average, the hourly markets offer better profitability prospects. Nevertheless, it's also important to acknowledge that in the FCR-N hourly market there are many zero hours when Fingrid doesn't buy any power capacity. This indicates that during these hours a battery would remain non-utilized and no income could be realized from the hours in question whereas in yearly market a battery could be operational round the clock. However, it has be noted that there is an important battery characteristic that favors the FCR-N hourly market over the yearly one: every time battery is operational it wears its machinery resulting in shorter life expectancy. This concept of battery's life expectancy is elaborated further in chapter 4.4.

The usage wear of a battery signifies that every time battery is operational it has to gain notable earnings that are sufficiently high enough in order to compensate the high investment costs. Consequently, as the average prices in FCR-N hourly market are higher than the fixed ones in yearly market, on average, a battery can have better income in relation to the wearing of its machinery. Thus, in hourly market a battery can operate much longer and simultaneously achieve better total profitability for an entire project. Nevertheless, the market share of power capacity in FCR-N hourly market is relatively small which means that a large-scale "battery rush" on that market could cause some saturation effects. However, there are currently no clear signs of short-term market share cannibalization in FCR-N hourly markets due to good adaptability of hydropower in different markets. On the contrary, the prices and capacity sizes in FCR-N hourly market have increased significantly during the year 2017 because the yearly capacity amount in FCR-N yearly market decreased explicitly, as seen in Table 3 (Fingrid, 2017e).

To sum up, from all the electricity market places in Finland the Fingrid's reserve markets give the most suitable and lucrative environment for battery operation. Furthermore, from different reserve markets the FCR-N hourly market takes into account the best characteristic of battery technology and offers the most profitable prospects for large-scale battery projects.

3 Battery Energy Storage System

As wind and solar power increase their share in electricity generation, there is a growing need for an economic intermediate energy storage between the volatile electricity generation and end-consumption. Apart from proposed energy storage solutions for converting electricity, large-scale electro-chemical battery storage systems have been considered as a potential solution for imbalance challenges and decreasing grid inertia. These biz-size batteries for grid-scale applications are academically known as battery energy storage systems (BESS) or alternatively battery storage systems (BSS). The battery energy storage system mainly consists of the battery packs, battery management systems (BMS), a single system supervisory control (SSC) and required converters. BMS operates to preserve both secure and optimal procedure of each battery pack whereas the function of a SSC is to monitor the whole energy storage system. (Lawder, et al., 2014) Figure 15 portrays a general structure, interconnections and their main functions inside a BESS application. Later on, Figure 23 will show a simplified illustration demonstrating the full architecture of an equivalent battery energy storage system.

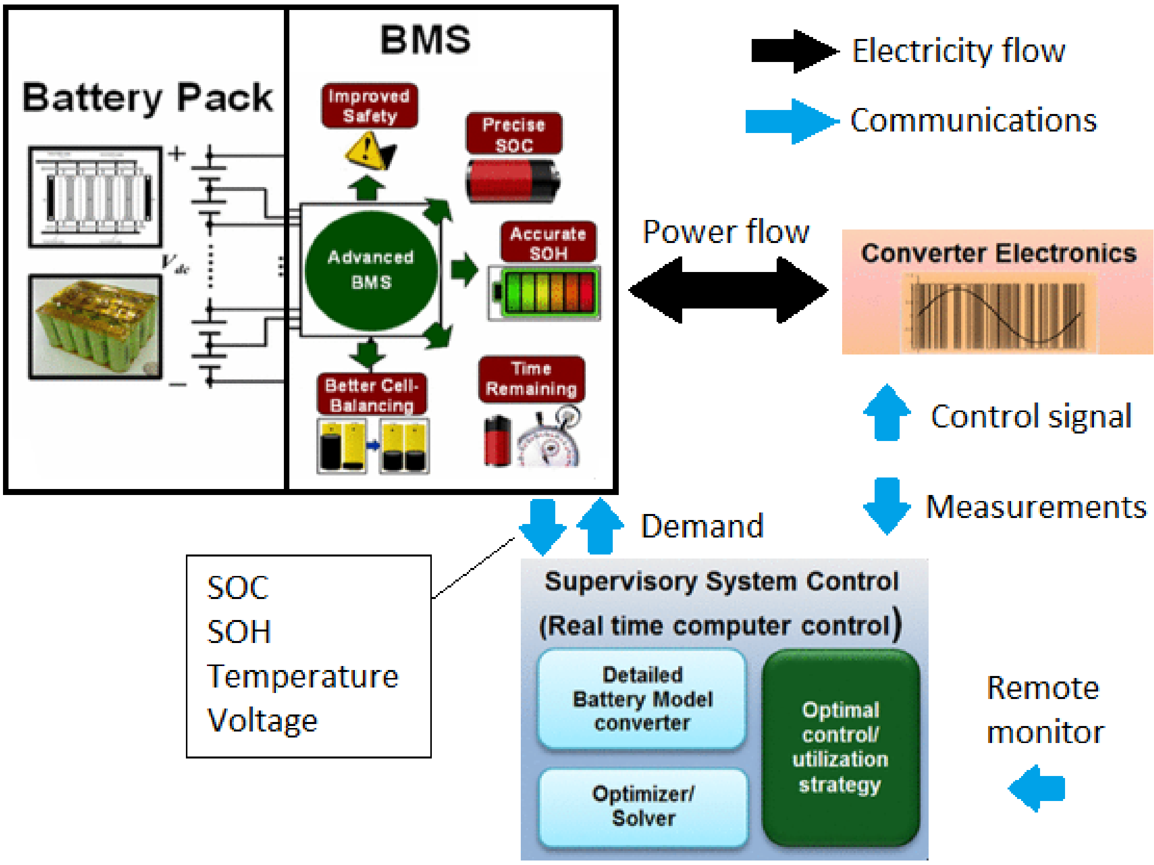


Figure 15: Schematic of a BESS implementation. Data source: (Lawder, et al., 2014).

3.1 *Battery technology*

The batteries are comprised of stacked cells where the chemical energy and electrical energy are converted to each other depending on the discharge or recharge of the system. By linking cells parallel and in series the desired features of voltage and current levels are achieved. Traditionally, the power and energy capacities of batteries have been dominating their ratings. In addition to them, other significant battery features are efficiency, lifetime expectancy with cycle numbers, operation temperature and energy density. (Divya & Østergaard, 2009)

3.1.1 Battery types

There are currently various battery technologies available in the market. Nevertheless, the ones that have enough mature technology and suitable usability for BESS applications are reviewed in this thesis. Furthermore, there are plenty more varieties of different battery subtypes with some changes in chemical substances but the principal categories are listed below. The battery types in question have been listed according to their technical maturity.

3.1.1.1 Lead acid type battery

Lead acid type battery consists of a positive anode of a lead dioxide (PbO_2) and a negative cathode of sponge lead (Pb). These electrodes are separated from each other with a micro-porous material and enclosed in a plastic case which contains electrolyte of aqueous sulfuric acid (H_2SO_4). When the lead acid battery is discharged the lead dioxide from the positive electrode is reduced and reacts with sulfuric acid to form lead sulfate ($PbSO_4$). Meanwhile, on the negative electrode the sponge lead is oxidized to lead ions which forms lead sulfate with sulfuric acid. This process occurs by the conduction of electrons which leads to generated electricity in an external circuit. (Divya & Østergaard, 2009) When the lead acid battery has been fully discharged both electrodes have gained layers of lead sulfate with diluted electrolyte of sulfuric acid. During the charging process the reaction is reversed. The lead acid battery's total chemical reaction of discharge is represented in Equation (1) and portrayed in Figure 16. (Hazza, et al., 2004)

$$Pb(s) + PbO_2(s) + 2\,H_2SO_4(aq) \leftrightarrow 2\,PbSO_4(s) + 2\,H_2O(l) \tag{1}$$

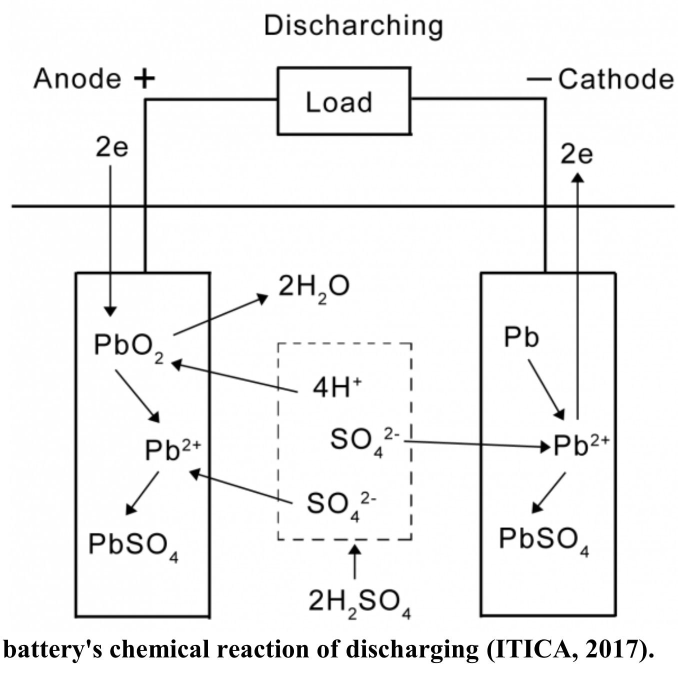


Figure 16: Lead acid battery's chemical reaction of discharging (ITICA, 2017).

3.1.1.2 Nickel cadmium type battery

Nickel cadmium (NiCd) type battery comprise of a positive electrode plate of nickel(III) oxide hydroxide (NiOOH), a negative electrode plate of cadmium (Cd), a separator and an alkaline electrolyte with potassium hydroxide (KOH). Nickel cadmium battery was invented in 1899 but lost its market share quickly to other rechargeable battery technologies in the 1990s. NiCd batteries were developed especially for smaller consumer use but they could also be utilized in large scale applications. When compared to lead acid type batteries NiCd batteries have poorer cell voltage but better energy density as well as longer life expectancy. Nevertheless, negative temperature coefficient, voltage decreases, high prices and environmental issues have made the NiCd batteries less attractive battery type for major investments when compared to other technologies. The chemical reaction of a NiCd battery is represented in Equation (2) and the structure is portrayed in Figure 17. (Soloveichik, 2011)

$$Cd + 2\ NiO(OH) + 2\ H_2O \leftrightarrow Cd(OH)_2 + 2\ Ni(OH)_2 \quad (2)$$

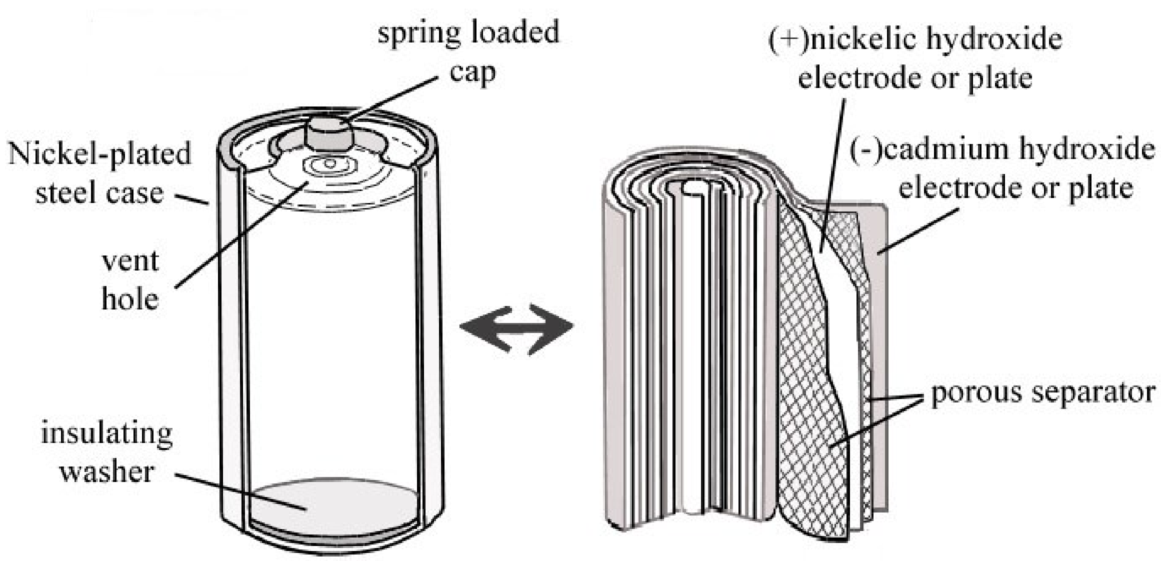


Figure 17: Structure of a nickel cadmium type battery (Intriere, 2016).

3.1.1.3 Sodium sulfur type battery

Sodium sulfur (NaS) type battery has at the positive electrode molten sulfur (S) and at the negative electrode molten sodium (Na). These are separated by a beta-alumina solid electrolyte which lets only the positive sodium ions to pass in order to form sodium polysulfide (Na_2S_4) with the sulfur. When the battery is being discharged the sodium atoms donate electrons for an external circuit and then flow through the electrolyte to the sulfur container. Here, the electrons react with sulfur forming negative sulfur ions which lead to the end products of sodium polysulfide with sodium ions. (Divya & Østergaard, 2009) The total chemical reaction is represented in Equation (3) (Zhaoyin, et al., 2008). The produced voltage is around 2 V and in order for the process to succeed the temperature has to be kept around 300°C (Divya & Østergaard, 2009). Nevertheless, the high usage temperature creates certain safety challenges as, for example, on 21 September 2011 the NaS batteries were responsible for a fire incident that happened at a power plant in Joso City, Japan (Dunn, et al., 2011). Lastly, structure of a sodium sulfur battery and its chemical reactions are portrayed in Figure 18.

$$2\,Na + 4\,S \leftrightarrow Na_2S_4 \tag{3}$$

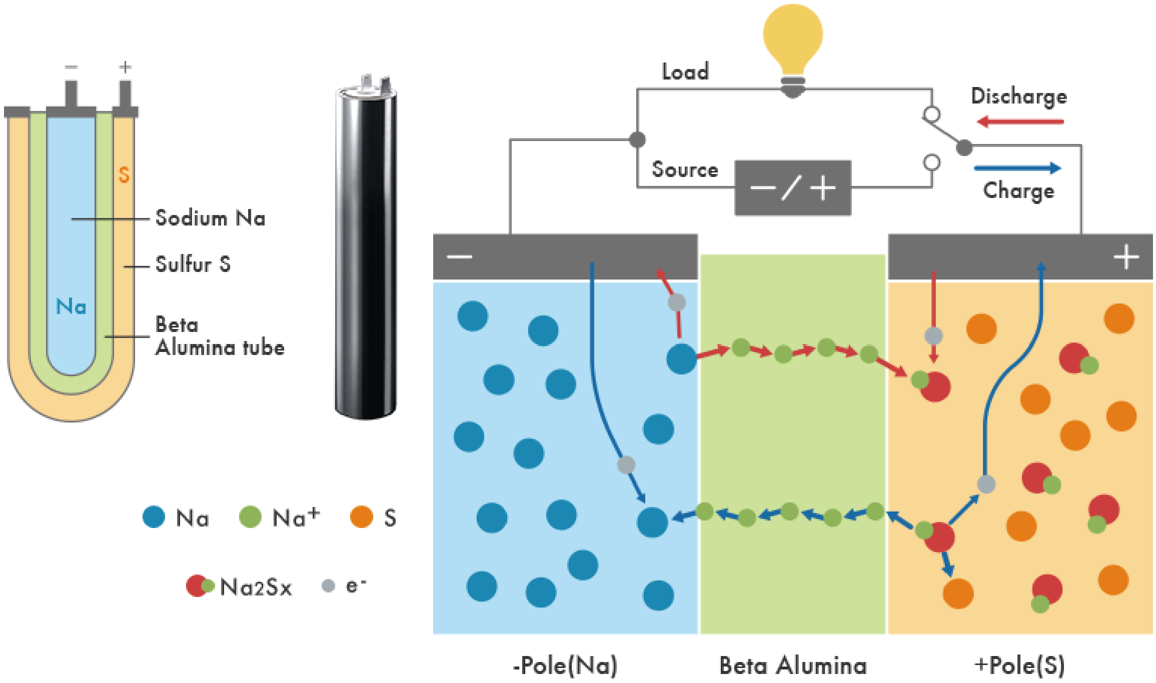


Figure 18: Sodium sulfur battery and its chemical reaction of discharging or charging (NGK Insulators, 2017).

3.1.1.4 Lithium ion type battery

Lithium ion (Li ion) type battery represents currently the most dominating technology for consumer and mobile applications and it is heavily developed in context of electric vehicles (Soloveichik, 2011). Li ion battery consists of positive cathode with lithium metal oxide, for example $LiMO_2$ or equivalent, and of negative anode with layered graphitic carbon (C). The electrolyte is composed of lithium salts that are dissolved in organic carbonites. During discharge the lithium atoms from the negative electrode convert to positive lithium ions (Li^+) and then migrate through the electrolyte to the positive electrode to reform lithium atoms. The electrons flow from the anode to the cathode creating electricity in an external circuit. During a charging process the reaction is reversed. (Divya & Østergaard, 2009) A generic chemical reaction between lithiated carbon and lithium metal oxide is presented in Equation (4). There are currently many Li ion technology subtypes in service and in development depending on its purpose of use. At present, there is a major research in replacing materials with restricting capacities to higher capacity materials. For example, if lithium carbon in anode is replaced with lithium metal the energy capacity could be 10 times bigger than in traditional Li ion battery. However, the poor Li reversibility still limits such applications. (Soloveichik, 2011) An example of chemical operations of a traditional lithium ion battery is demonstrated in Figure 19 which represents exactly the same subtype as used in Batcave battery storage system.

$$Li_xC + Li_{1-x}MO_2 \leftrightarrow LiMO_2 + C \tag{4}$$

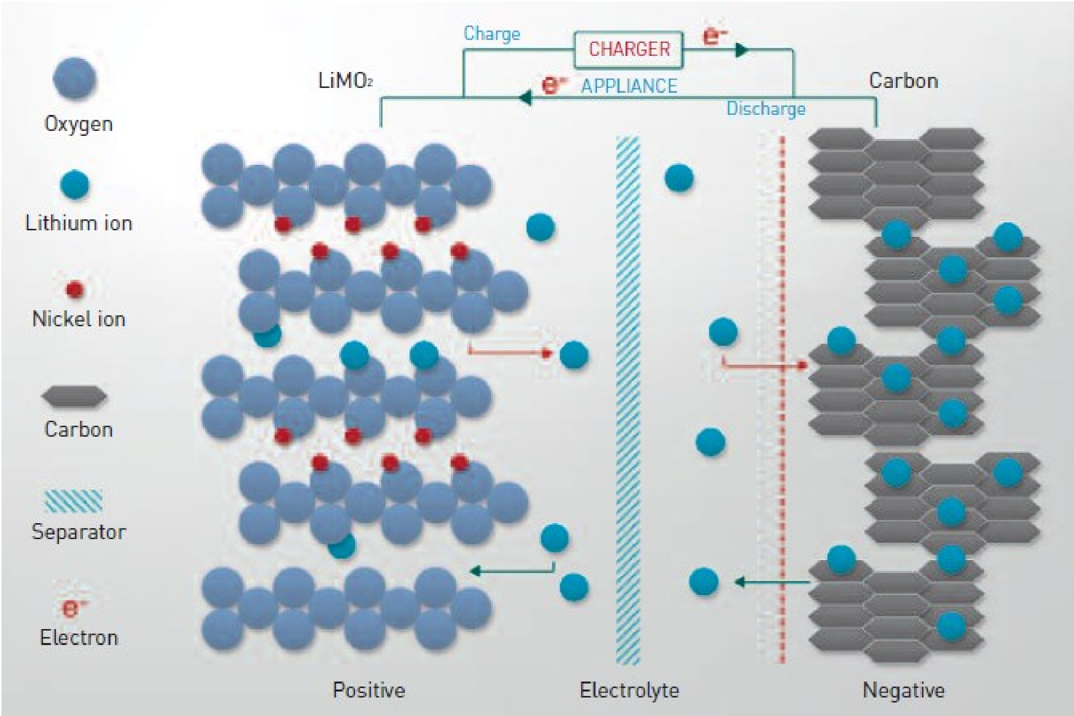


Figure 19: The principle operations of a lithium ion battery (Saft, 2014a).

3.1.1.5 Metal air type battery

Metal air type battery creates electricity flow by means of a redox reaction between metal and oxygen (O2) that can be found in air. The battery includes a negative anode made of metal, usually categorized as zinc (Zn), magnesium (Mg), aluminum (Al) or lithium (Li). The advantages of the crude materials of Zn, Mg and Al is that they are easily available, relatively affordable and pose a high theoretical energy density. (Cheng & Chen, 2012) Furthermore, the positive cathode is managed as air and it's usually constructed as an open cell structure, generally from a porous carbon or metal mesh. The electrolyte is composed of either a liquid form or a solid polymer with good conductor capabilities of hydroxide ions (OH^-). (Divya & Østergaard, 2009) In discharging state of the battery the negative electrode of metal releases electrons to the external circuit. Simultaneously, oxygen accepts the electrons in the positive electrode and is reduced to form metal oxides with metal ions that have migrated through the electrolyte. During the charging process the reaction is reversed. The electrochemical reactions of metal air type batteries are represented in Equations (5) - (8). As the solubility of oxygen is weak in liquid electrolyte the electrochemical reactions occur largely at the liquid-gas-solid interface of a catalytic cathode. (Cheng & Chen, 2012) A representation of a metal air battery and its electrochemical reaction interface is demonstrated in Figure 20.

$$2Zn + O_2 \rightarrow 2ZnO \tag{5}$$

$$2Mg + O_2 + 2H2O \rightarrow 2Mg(OH)_2 \tag{6}$$

$$4Al + 3O_2 + 6H_2O \rightarrow Al(OH)_3 \tag{7}$$

$$4Li + O_2 + 2H_2O \rightarrow 4LiOH \tag{8}$$

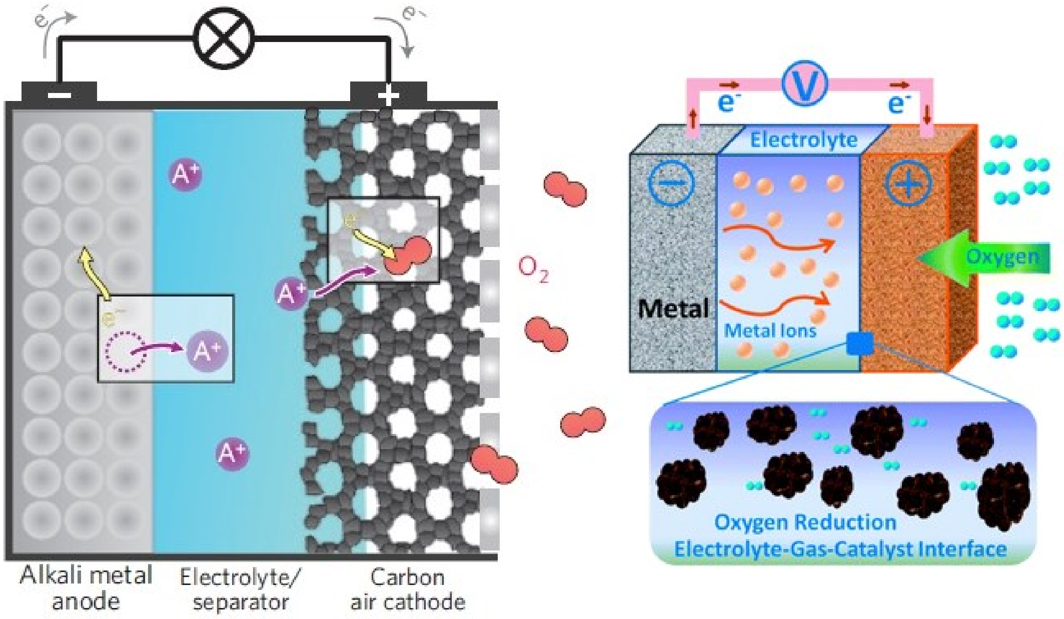


Figure 20: Structure of a metal air type battery and its liquid-gas-solid reaction interface. Left source: (Hartmann, et al., 2012) and right source: (Cheng & Chen, 2012).

3.1.1.6 Flow type battery

The flow type battery concept has been in observation since the 1970s but it's still considered as the least mature technology when compared to other batteries (Soloveichik, 2011). Flow type battery comprise of two tanks of electrolyte from which the liquids are pumped past an electrochemical cell that contains an negative anode, positive cathode and an ion-selective membrane that separates them. When the two electrolytes circulate throughout the electrochemical cell electricity is produced and coveted from the chemical energy. The energy density is defined by the size of the two electrolyte reservoirs and the power density is determined by the reaction rates on the negative and positive electrodes. The flow batteries are also been referred as redox flow batteries because of the reduction-oxidation reaction that occurs with the two electrolytes. The three main types of flow type batteries are regenerative fuel cell of vanadium redox battery (VRB), polysulphide bromide (PSB) and zinc bromine battery (ZnBr). (Divya & Østergaard, 2009) The Vanadium redox battery was proposed for the first time at the University of New South Wales, Australia in 1984 and it's nowadays considered as the most mature type of flow batteries. The VRB electrochemical reaction of redox couples in sulfuric acid is represented in Equation (9). The most interesting aspect about the flow type batteries is the possibility to separate the energy capacity from the power capacity which allows to design more tailor-made characteristics for a BESS application. However, low energy density of electrolytes, risk of cross-contaminations and membrane endurance restrict wider services for flow type batteries. (Soloveichik, 2011) The basic operation function of a flow type battery is portrayed in Figure 21.

$$VO_2^+ + 2\,H^+ + V^{2+} \leftrightarrow VO^{2+} + H_2O + V^{3+} \qquad (9)$$

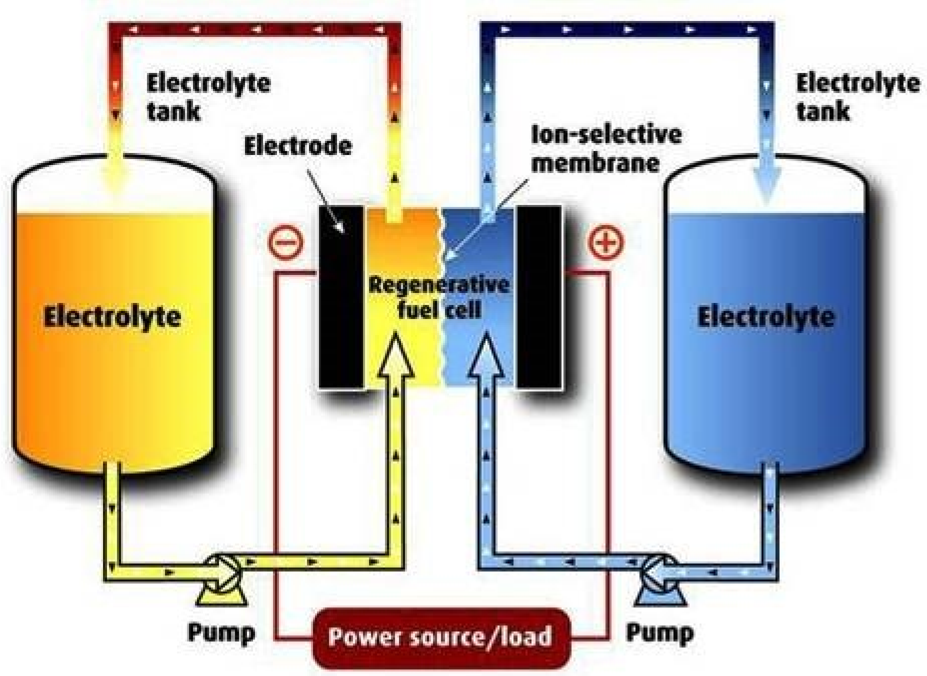


Figure 21: Operation schematic of a flow type battery (Nordic Folkecenter for Renewable Energy, 2009).

3.1.2 Battery comparisons

When considering different battery types, the lead-acid battery is the oldest and it has been applied for a great share of power system applications. The lead-acid and NiCd batteries supply great power impulses but nevertheless they require a lot of space, include toxic heavy metals and easily discharge themselves when not used.

NaS battery, with great power density, has however high operation temperature and requires uninterrupted heat availability in order to keep the process functioning. Additionally, the metal air batteries have, beside the high energy density, low manufacturing costs but it’s challenging to recharge them.

Because of the non-self-discharging capabilities, flow batteries appear promising for long duration storages. Nevertheless, the costs of chemical plant operations with pump systems and external reservoirs decrease the profitability of flow batteries. The major future development is concentrated on increasing the power density of flow batteries.

Li ion batteries show the most promising potential for future development as well as optimization. Li ion batteries are light with the highest energy density and great storage efficiency. However, the deep discharging of battery has harmful effects on its lifetime and additionally they are expensive because of the complex manufacturing process of protection circuitry. (Divya & Østergaard, 2009)

A list of the standard characteristics of different battery types can be found in Appendix 2. Moreover, Figure 22 portrays a diagram of power and energy densities of different battery technologies. As it can be seen from Figure 22, if looking solely on power and energy densities, the Li ion batteries seem as the most suitable technology at the moment for grid-scale energy storing.

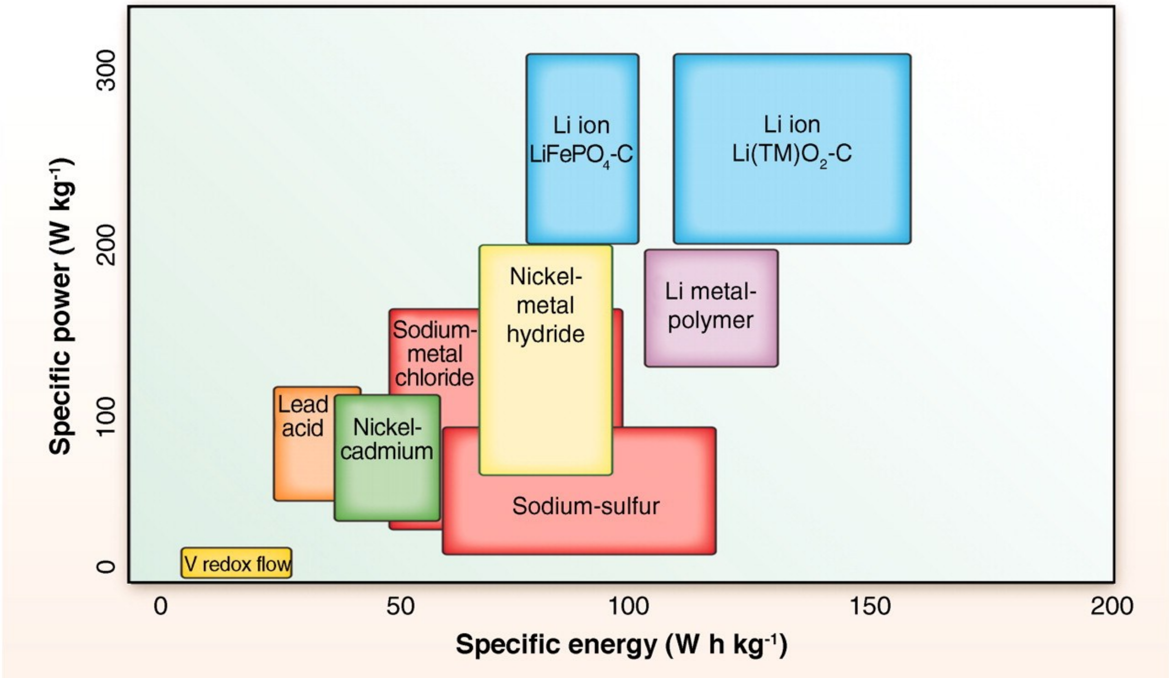


Figure 22: Diagram of power and energy densities of different battery technologies (Dunn, et al., 2011).

3.2 Battery Management System

Batteries operate dynamically and during functions of discharging or charging they function continuously outside a static state. The closed battery system displays only some measurable state variables which makes it challenging to properly monitor the whole battery condition. Moreover, unfavorable operations accelerate the degradation of battery system such as extreme charging processes, high temperatures as well as undercharging and overcharging. Nevertheless, a model-based Battery Management System (BMS) can lead to decreased degradation effects and to enhanced system performance. The main function of a BMS is to manage the overall operation of batteries.

BMS can’t access to the internal states of battery cells and the only measurable conditions are voltage, current and temperature. Nevertheless, the BMS can accurately evaluate many required internal variables with physics-based models, for instance the state of charge (SOC) and the state of health (SOH) as seen in Figure 15.

One of the main responsibilities of BMS is to secure operations with thermal control and voltage management in order to switch off the system in case of a fault detection. Furthermore, the state estimation with SOC, parameter estimation with SOH and other various functions belong to the remit of BMS. (Lawder, et al., 2014)

3.3 Other BESS components

The information interface between a BMS and the electric grid is implemented with a system supervisory control (SSC). When the alternating current (AC) grid needs supplied power from battery the SSC operates the optimal discharge protocol depending on the SOC and the demand value. Different charging profiles of SSC can be created in order to satisfy various power management methods from the grid.

A representative grid storage solution (GSS) consists of direct current (DC) battery systems, their units of BMS, power conversion systems (PCS), an overall SSC, grid connection equipment and other smaller components. A simplified illustration of a GSS is presented in Figure 23.

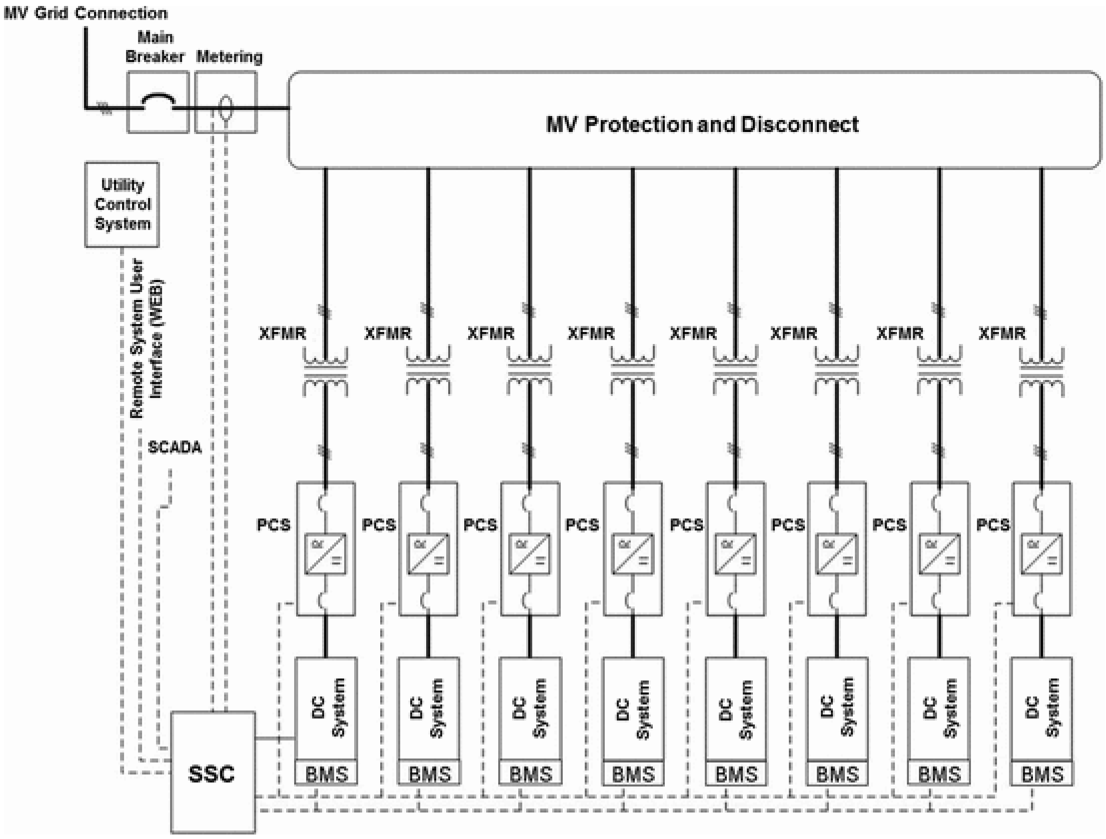


Figure 23: Simplified illustration of Grid Storage Solution architecture connected to the medium-voltage grid connection (Lawder, et al., 2014).

Inside a battery dc system the separate cells are combined parallel and in electrical series to form individual modules. These modules are assembled systematically to form a desired DC system that supports the application requirements. The DC battery system has an interface with a PCS, a four-quadrant ac-dc converter, and together they are linked to the AC grid via a transformer (XFMR). (Lawder, et al., 2014) The bidirectional ac-dc converter is required to attain, beside power flow capability requirements, notable power factor and unimportant total harmonic distortion (Qian, et al., 2011). The whole unity of electrical components that include a DC system, a PCS and a transformer is often referred to as a power block.

The function of a BMS is to operate its own power block and SSC coordinates the totality of all the power blocks. BMS supervises the different signals from external sources concerning the DC system and SSC calculates the required discharge and charge responses and transmits the commands to the system. SSC functions as an intermediate of process operation and guiding batteries depending on the grid requirements. When IT intelligence is already concentrated on the lower level supervision system the main site controller has to monitor only the necessary information which decreases the overall information traffic. (Lawder, et al., 2014)

3.4 Future of battery energy storage systems

The future of battery energy storage system relies on how well the technology can meet its expectations. The main points of battery success can be listed as low installation costs, good life expectancy, high reliability and great operation efficiency. It's likely that as the competition in the battery industry increases there will be more importance on inexpensive and easily acquired materials and on simple manufacturing process alongside with easy-to-install features. Furthermore, in order for the battery storage systems to be profitable the lifetime expectancies and operation efficiencies have to be on an acceptable level. As so many economic aspects and uncertainties are in place it's not surprising that the battery energy storage systems are not that widely implemented on grid balancing. (Dunn, et al., 2011) However, during recent years the financial requirements of battery energy storages seem to have reached a certain satisfactory grade as more and more new systems have been installed and will be built across the globe. (DOE Global Energy Storage Database, 2017)

In order for the battery storage systems to be profitable enough for reserve markets, the manufacturing costs have to decrease sufficiently. It can be stated that the traditional and expensive battery manufacturing for industrial use has developed slowly during the last century when compared to the other electronic appliances. However, the development of Li ion batteries for electric vehicles and commercial electronics has boosted its major storage characteristics that are also equally significant for the battery storage systems. Besides the active battery research environment, it's probable that the most important aspect of battery development will emerge from the serial production of electric vehicles. A massive manufacturing process of electric vehicles can offer the needed economy of scale that will decrease the high costs of battery production. (Dunn, et al., 2011) A great example of this is when Tesla started developing electrical cars for consumers in a large scale the investigations on decreasing the battery cost started at full speed. Consequently, there has been a significant fall-off in battery costs during recent years. In six years the electric vehicle battery cost have dropped dramatically with 77 %, which can be seen in Figure 24 (McKinsey & Company, 2017). The most recent claim from Tesla company is that they have reached a new record low price level for Li ion batteries: 125 $/kWh in their newest Gigafactory at Nevada (Electrek, 2017). Consequently, it seems quite likely that the battery prices keep on falling in the future. Furthermore, it's also possible that the Li ion batteries of used electric vehicles could be used as large-scale, concentrated "second life" battery energy storage systems which could further ameliorate the circular economy of batteries. (Dunn, et al., 2011)

If the cost decreasing trend of electric vehicles continues at same pace while having direct influences to the manufacturing costs of batteries, the battery storage systems can soon have fairly profitable business cases in reserve markets. Nevertheless, as the market share of power capacity in reserve markets is generally relatively small, a large-scale "battery rush" on that market could cause some saturation effects. That's why constant examinations on long-term market developments have to be conducted in order to evaluate as truthfully as possible the profitability prospects of battery storage systems. At the moment, different energy companies are ready to examine battery energy storage applications and their possibilities in different reserve markets. As compared to traditional power plant projects that require long construction periods, battery storage systems can be built relatively fast.

This means that if there is a clear market space for battery projects it's highly probable that those opportunities are rapidly exploited. Good example of this can be found in the United Kingdom where the National Grid designed a new Enhanced electricity market especially for battery operations in 2016. However, there was a massive rush for that market, as for the 200 MW size auction there were over 1 200 MW worth of bids which decreased the prices extremely low and thus making the projects not especially profitable (Steel, 2017). The coming years will show how the UK's Enhanced market will develop.

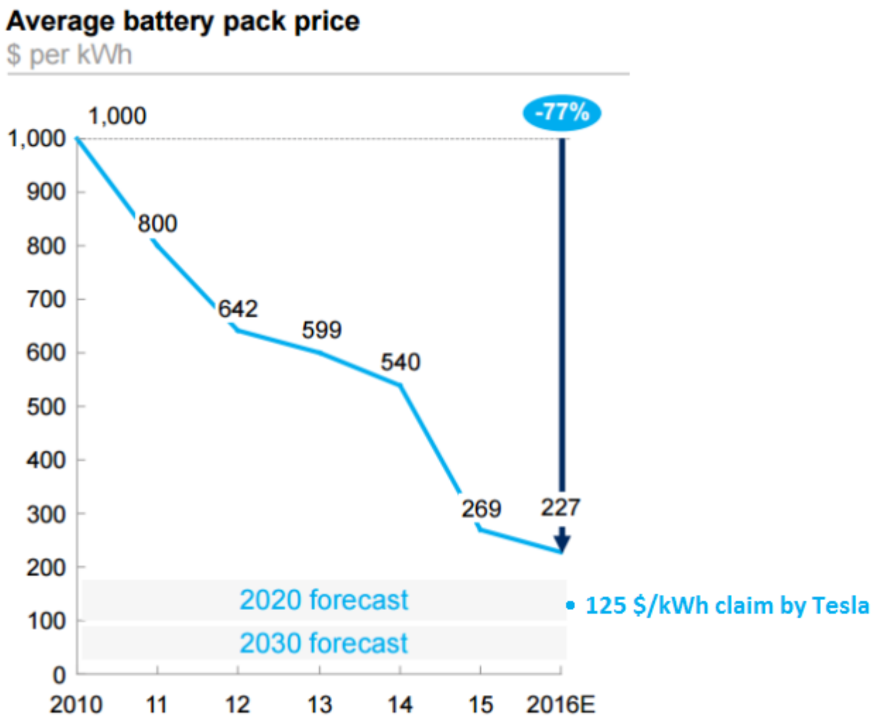


Figure 24: Average battery price evolution between the years 2010 - 2016. Data source: (McKinsey & Company, 2017) and (Electrek, 2017).

Currently batteries work well in reserve markets where instant power effects to the grid are required for relatively short time intervals. However, because battery technology is still expensive and has quite restrictive energy capacity sizes they don't suite well in huge energy volume transmission requirements. This means that as solar and wind energy increase their share in the energy mix, batteries cannot compensate alone the production uncertainty of renewable energy sources with current price levels. However, if the battery costs decrease substantially and the volatility of spot-values escalate enough in physical markets alongside with good price-predictability programs, batteries could provide economical solutions to day's lasting energy peak shaving. Yet, until that occurs, batteries can continue to regulate micro-shifts in grid frequency and take advantage of their power capacities for short-term reserve markets. Respectively the battery operations will get improve for future applications with iterating processes of optimization.

According to the general view and analyses, the amount of electrochemical batteries will grow globally. It's forecasted that the installed power capacity of battery storage systems connected to the grid will increase from 1,5 GW in the year 2015 to over 14 GW by 2020 (GlobalData, 2016). Furthermore, when comparing centralized and decentralized systems, energy companies seem to prioritize utility-scale market positions with centralized "in front of the meter" applications, such as Batcave-project is. That's mainly because the frequency containment markets continue to offer the best short-term opportunities and profits for electricity storages. It's estimated that in 2017 the concentrated energy storage solutions account for 76 % of the total market. Nevertheless, when battery costs keep on decreasing sufficiently customers become more and more interested in their own "behind the meter" storage applications. This helps to smooth and enhance their co-located solar power installations with constantly rising demand charges. (Steel, 2017) When the producers and customers become more and more interested in electricity storing systems the number of batteries could explode in quantity. Moreover, as the inverter investments are much cheaper in smaller voltages than in large-scale applications, the total investment costs could favor decentralized systems in the future. Thus, it's quite possible that with different virtual power plant concepts and demand-response applications the battery energy storage systems could shift from big concentrated utilities to decentralized solutions. With expected rising energy price volatility they could provide an important regulative power capacity for the grid balancing if operated together optimally.

As the electrochemical batteries represent a quite new application for large scale grid-balancing markets the European Commission has issued this subject in a legislative point of view. The definition of energy storages for the new market design legislative measures is on its way and the year 2017 will present a major phase for the battery advocacy at the institutions of European Union. (Steel, 2017) Since the common market rules are still fairly extensive and the battery technology is yet relatively expensive, energy companies try to find different ways to aggregate, as broadly as possible, the value of their battery storages. For example in Europe, because TSOs and distributers can't own, manage or operate their own battery systems, TSOs could however buy this service from third parties. Grid connected battery systems improve the reliability of power-distribution networks which help to postpone possible grid enhancing investments. For example In Berlin the German Institute for Economic Research has evaluated that 6,1 billion euro investment is required for its grid network by the end of 2020 in order to ameliorate the forthcoming unpredictability (Bertram, 2017). Thus, TSOs have actual interests to find low-priced alternatives for grid investments. As the German's 600 MW primary reserve markets have already begun to saturate the battery owners and grid operators could have a common interest to find synergic solutions and alliances (Schramek, 2016). Consequently, in battery storage business different systems and solutions of shared benefits are anticipated to grow in general.

4 Case Batcave

The cumulative investments in renewable energy sources with volatile production estimates have led to raising interest in electrochemical batteries and their possibilities in equalizing the grid fluctuations. When compared for example to Germany, Finland and other Nordic countries have implemented some small-sized batteries that are yet more considered as research projects. However, during April 2016 Fortum, a Finnish energy company, informed that it launches a battery energy storage project that will be the biggest battery system in the Nordic countries after its completion (Fortum, 2016). This gave an excellent opportunity to study how this large-scale battery, later on named as "Batcave", would operate in power reserve markets and how its different profitability scenarios could be structured. Figure 25 represents the basic concept of the installed Batcave energy storage and its relations.

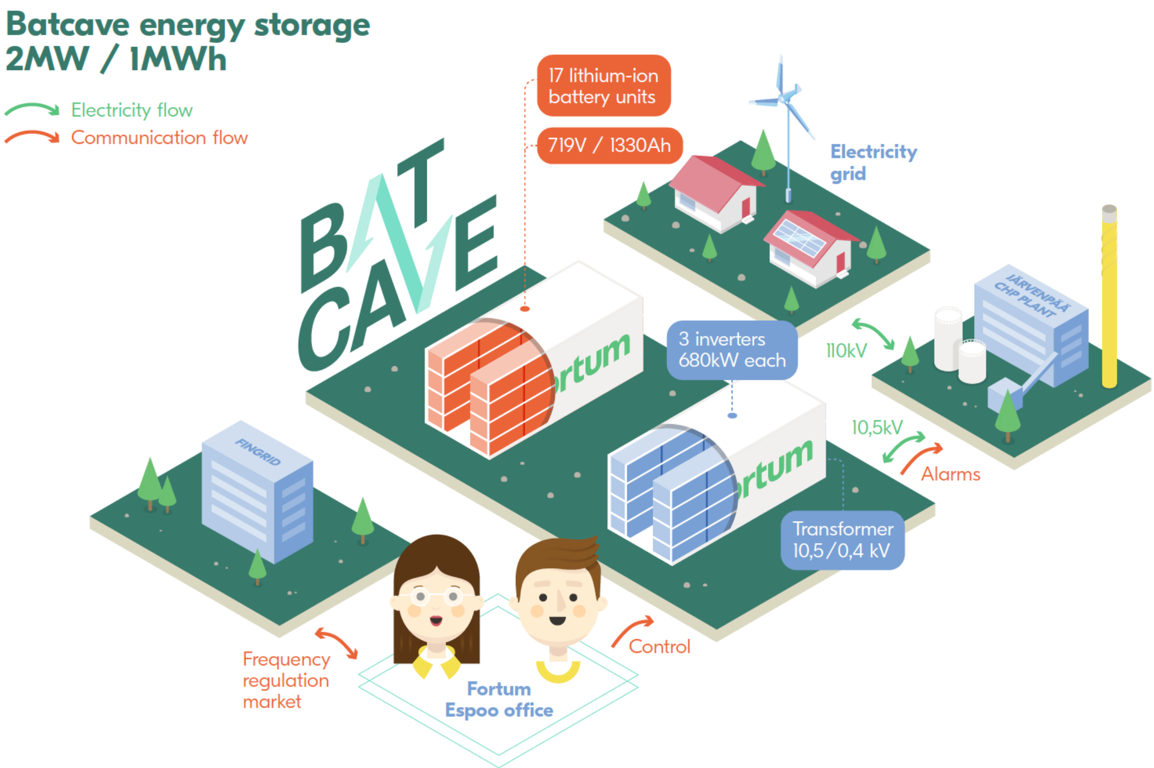


Figure 25: Concept illustration of Batcave energy storage (Fortum, 2017b).

4.1 Introduction

Fortum's battery project was named as Batcave which refers to the abbreviation of the word “battery” and to rephrasing of the word “container” (as cave) where the actual battery is situated. The Batcave energy storage is installed inside the domain of Fortum’s bioenergy power plant in Järvenpää, Finland and the battery system in question started operating on March 1st 2017 (Fortum, 2017b).

The main function of the Batcave project is to have a research and development project about concentrated large-class battery technology and to evaluate its operating properties for grid power balancing. Additionally, economical possibilities and benefits with hydropower are also investigated in the Nordic reserve markets. (Fortum, 2016)

The investment cost of the Batcave project is around 1,6 million euros and the Finnish Ministry of Employment and the Economy (TEM) granted financial support of 30 % for it. The project started in April 2016 and the ensemble was carried out during March 2017. (Fortum, 2016) Figure 26 shows a picture of Batcave energy storage that is taken from the Järvenpää bioenergy power plant.

Figure 26: Picture of the Batcave battery storage system (Fortum, 2017b).

4.2 Technology

The battery itself was manufactured by Saft in Bordeaux, France and it was delivered from France to Finland during November 2016. The Batcave battery is a lithium ion type battery with energy capacity of 1 MWh, maximal power capacity of 2 MW and C-rate of 2,2 C. (T&T, 2016) In battery specifications the C-rate indicates the quantity of charges or discharges that the battery is hypothetically capable to operate during one hour (Garcia, et al., 2004). Manufacturer has estimated that the battery's round trip efficiency for frequency regulation application is at the beginning around 98 % and still after 10 years at 96 %.

The lithium ion cells of the Batcave battery have positive electrodes with lithiated metal oxides ($LiMO_2$) and the negative electrodes are manufactured from carbon material. The electrolyte consists of lithium salts that that are dissolved in organic carbonites. Furthermore, the separator is made of porous polymeric materials. (Saft, 2014a) The electrochemical process of Saft's Li ion battery is portrayed in Figure 19.

The battery is situated inside a container that is 6 m long, 2,3 m width and 2,4m high. The container includes 17 energy storage system strings connected in parallel and assembled in racks. Furthermore, every system string include 14 modules and there are 28 lithium ion cells inside every module. (T&T, 2016) The cells are compiled in series and in parallel assembly in order to provide the required voltage and energy capacity (Saft, 2014a). The representation of battery container's architecture is illustrated in Figure 27.

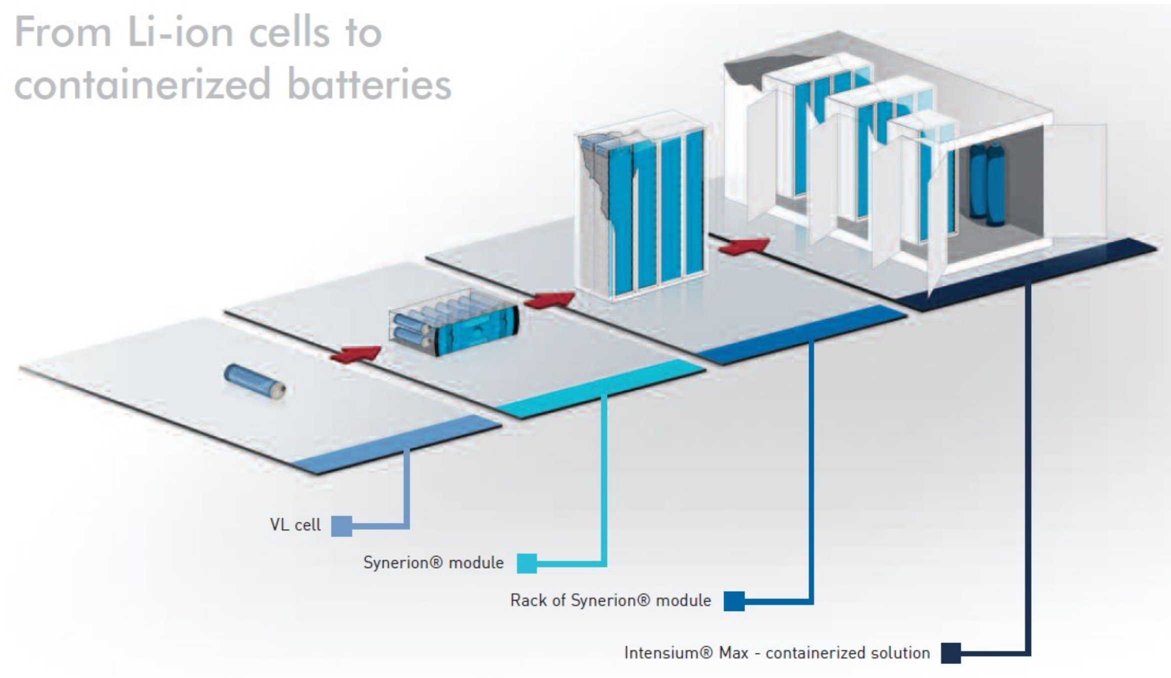


Figure 27: Representation of battery container's architecture (Saft, 2016).

The power conversion system is placed inside another container and it is located next to the battery container. The power conversion container consists of dc-ac inverters, a converter controller, circuit breakers and a programmable logic controller that controls voltage and power values. The power conversion system was manufactured by Schneider Electric. (T&T, 2016)

According to the battery manufacturer, the ideal internal temperature of battery is around 25 – 55 °C and below 0 °C the energy capacity starts to derate. Therefore, the battery container has its own heating and air conditioning system functioning with auxiliary power in order to maintain its optimal operation temperature. The HVAC system keeps the inside temperature of container at 10 – 30 °C depending on the internal and external conditions. Additionally, the container includes a fire suppression system in order to prevent any faulty situation or incident. (T&T, 2016)

4.3 Communication

Each module of Batcave battery has its own safety monitoring unit that balances the internal cells and supervises their voltage and temperature values. Individual modules are connected in series and this system string unity is linked to one battery management system. In Saft's energy storage products the battery management systems (BMS) are referred to as battery management modules (BMM).

The one main role of the BMM is to manage all the modules inside the system string rack with voltage, temperature, current and alarms. Secondly, the BMM manages the maximum currents that are authorized during the processes and safely disconnects the system string in case of danger. All the BMMs are connected to the higher communication system called master battery management module (MBMM).

All the Batcave's 17 system strings with BMMs are connected in parallel to the MBMM. The MBMM calculator is in charge of gathering data and delivering key information to the customer's interface, including state of charge (SOC), state of health (SOH) and available power. The MBMM is situated inside the battery container and it communicates simultaneously with the fire suppression unit as well as with the HVAC system. (Saft, 2014a) A simplified schematic of power and data connections inside the Batcave battery is illustrated in Figure 28.

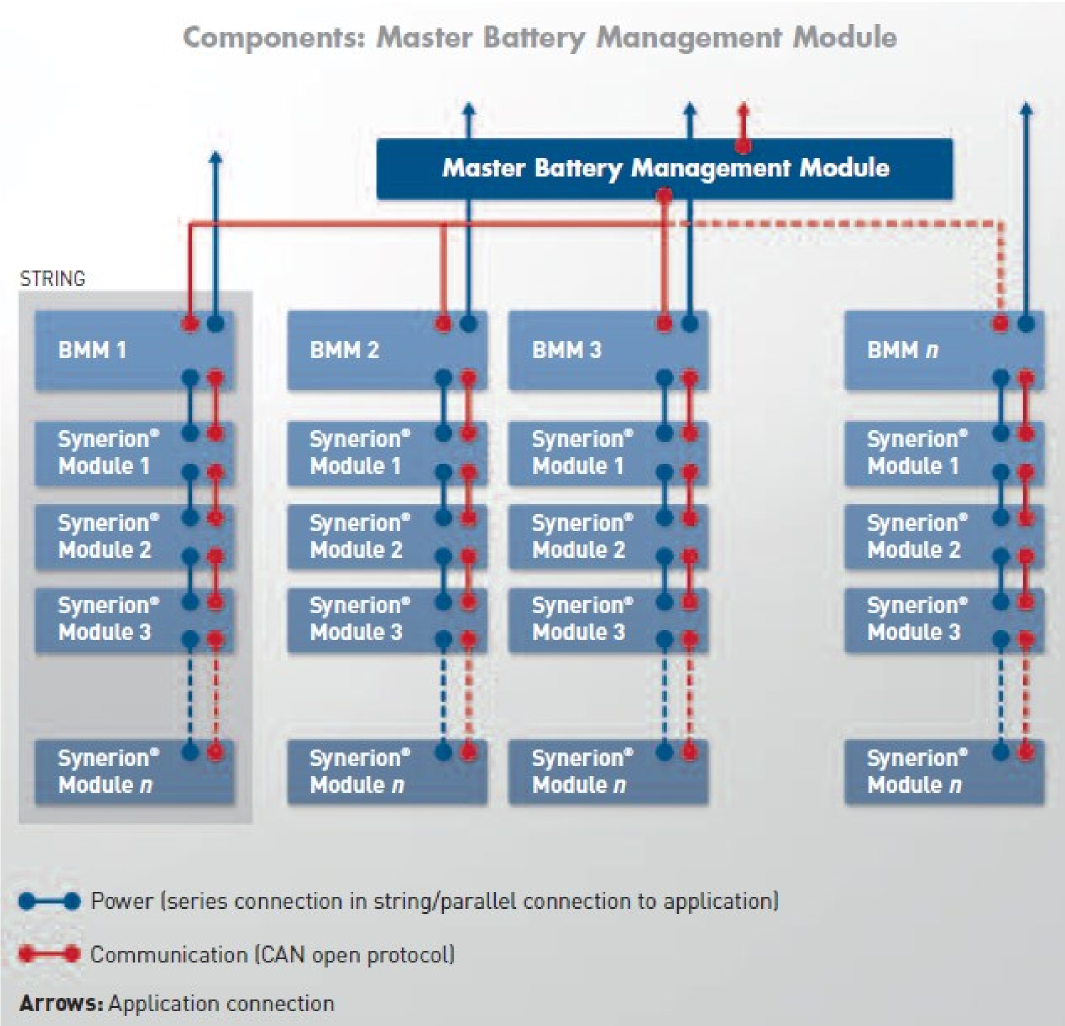


Figure 28: Schematic of the power and data connections inside the Batcave battery (Saft, 2014a).

4.4 Battery life expectancy

Li ion batteries don't express "sudden-deaths" like traditional lead acid batteries but instead their performance will degrade gradually. Generally, the end-of-life (EOL) state is described as a fall of 20-30 % in its initial energy capacity. Even after achieving the EOL-level the battery isn't completely unusable but it has achieved its preliminary stage in which its original operation aims are at risk. Information about the Batcave's state of health (SOH) is constantly available thus enabling to evaluate efficiently when the battery has reached its EOL-stage.

Two distinct aspects can be sorted out when considering the life expectancy of batteries: calendar life and cycle life. Saft has been testing its Li ion batteries in long term lab experiences and during different projects by independent research institutes. This has led into battery aging aspects in question which are described in more detail below.

Calendar life indicates how long the battery would last functional despite the abrasion of passing time. The main factors that have an influence to the calendar aging are the state of charge (SOC) as well as the operating temperature. The SOC-level indicates that how fully the battery is charged with when it's in a stored stage. Furthermore, for experiments to have credible results in shorter test times the operation temperatures are held in unusually high values. (Saft, 2014b) The proportions of SOC-levels and operation temperatures to calendar aging are demonstrated in Figure 29.

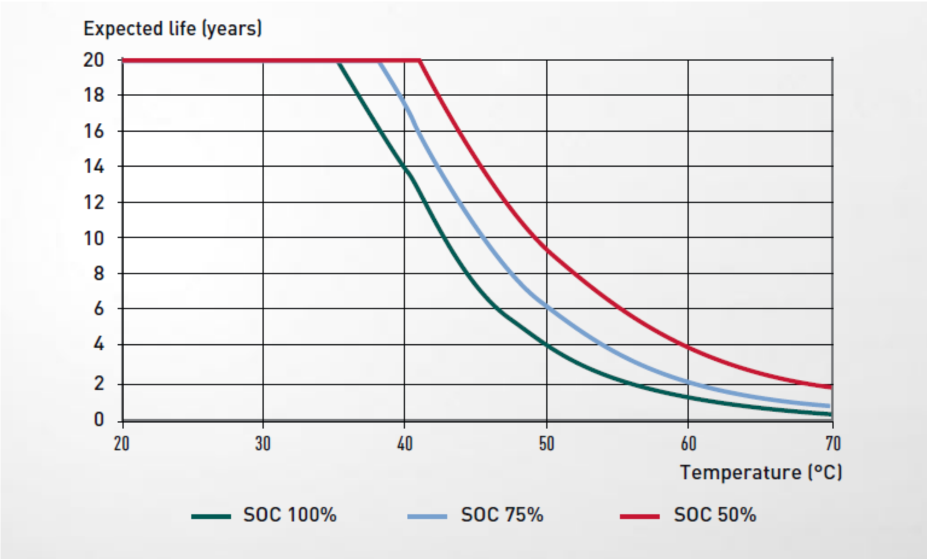


Figure 29: Calendar life expectancies of Li ion cells in relation to the operation temperatures with different maximum SOC-levels (Saft, 2014b).

Figure 29 represents that the lower the battery's maximum SOC-level is kept in stored stage the better its calendar life expectancy is. Furthermore, under normal operational conditions of 20-30 °C the calendar life expectancies of Saft's Li ion batteries are clearly over 20 years regardless of the SOC-levels. Furthermore, because the surveillance of battery management modules is engineered to make sure that the cells operate continuously at an average temperature of 25 °C it can be assumed that the calendar life expectancy of Batcave battery is in excess of 20 years. However, it is beneficial to constrain the occurring calendar aging effect in such a way that the battery should never reach its full SOC-level.

Cycle life indicates the number of cycles that the battery can endure before reaching its end-of-life stage. One cycle unit is counted when the whole battery energy capacity has been at first fully charged and then completely discharged. The main indicator that has an effect on the cycle life is the depth of discharge (DOD) that indicates the percentage of battery's discharge level. In other words, DOD is a reciprocal function of the SOC-level which means that if DOD-level is 0 % the battery is completely full and in 100 % DOD-level the battery is entirely empty. (Saft, 2014b) The influence of DOD-level on battery cycle life is represented in Figure 30.

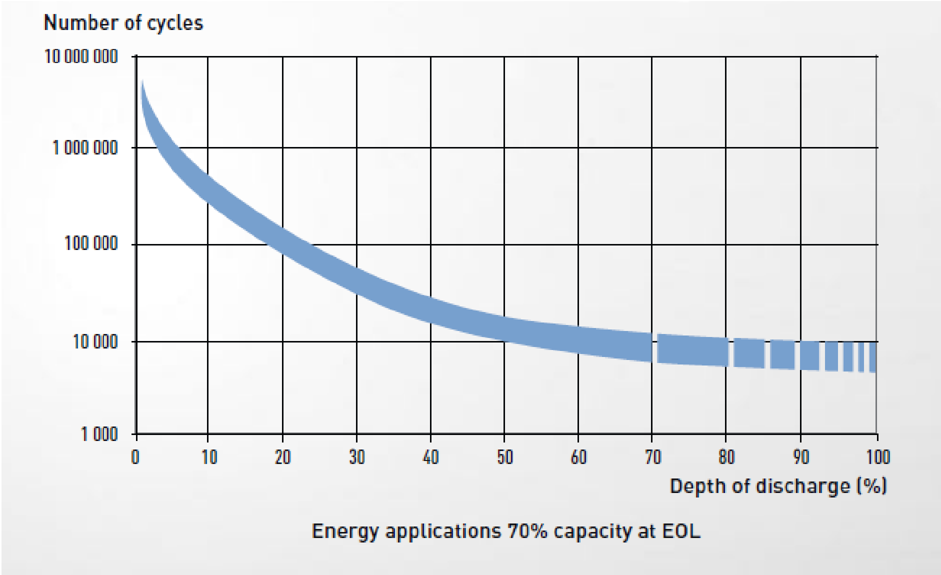


Figure 30: Cycle life expectancy in relation to the depth of discharge at an average temperature of 25 °C (Saft, 2014b).

As it can be stated from Figure 30 it is favorable for the battery's lifetime expectancy if the battery is never completely empty. The more energy capacity is left inside the battery during the discharge operation the more it is likely to have longer life expectancy. The same applies also for never charging the battery at full state in order to prolong its life expectancy. For normal battery operations the limiting number of cycles will have a significantly more important role on the lifetime expectancy than the calendar aging. Thus, when estimating the lifetime expectancy of Batcave battery the cycle count should be the major indicator in its definition.

In order to maximize the lifetime expectancy of Batcave according to the calendar aging and, above all, the cycle aging the battery operation is designed so that it will never reach neither full nor empty stage. Furthermore, it has been decided that 10 % buffers will be left for the boundary limits of Batcave's energy capacity. This prolongs efficiently the life expectancy of the battery without liming too much the operation possibilities with available energy capacity. This is described in more detail in Chapter 5.3.1 that covers the operation model of Batcave battery.

5 Batcave simulations

The use of large-scale batteries in Finnish power reserve markets is a rather new application and thus there is no historically established practices to operate batteries in the most efficient way. Consequently, in order to make most of the Batcave battery system different simulation scenarios were conducted to find the best operation possibilities and the most profitable cases. As no real battery activity data is yet available for optimization calculations the simulations were ran to estimate how the battery would have been operational during the year 2016. The Batcave modelling and simulations were done with Microsoft Excel software and all the needed programming was conducted with its built-in Visual Basic for Applications (VBA) implementation.

5.1 Simulation data

For the Batcave simulations the frequency measurement data from the whole year of 2016 was used. It was obtained from Fingrid's web page and the data was packed into daily CSV-files. The frequency is metered at 400 kV substations at different Finnish locations and the frequency points are registered every one hundredth of a second. The data contained some minor gaps because of the telecommunication errors yet they didn't occur too often to have any larger impact on simulation results. (Fingrid, 2017a)

Nevertheless, the available time data was too precise which led in excess amount of data and in simulation difficulties. Therefore, the data points were filtered to show frequency measurements every second instead of an one hundredth of a second. The shifts between second points aren’t as smoot as with every hundredth of a second points but the precision still remains accurate enough in order to operate reliable simulations.

5.2 Simulation scenarios

The simulation of Batcave battery was conducted in the FCR-N hourly markets. This market was chosen because, from all the Finnish reserve markets, it provides technically the most suitable requirements for batteries and offers the best profitability possibilities as described in Chapter 2.3.2. Additionally, Batcave's characteristics are very suitable for FCR-N markets as the battery can activate rapidly in case of frequency changes and operate according to both up- and down-regulations.

The FCR-N market has two possible contract types: yearly and hourly market. The hourly FCR-N market was chosen for the simulations as it provides better income prospects per operation hour than yearly market. Moreover, every time battery is operational it causes inner aging which leads to the fact that the earnings per hour have to be adequate enough in order to compensate that abrasion.

For the Batacve simulations two principal scenarios were chosen for this task: All-scenario and Hydro-scenario. They represent the two principal operation manners regarding how the Batcave battery have been planned to function in the FCR-N hourly market. By studying closely these peripheral conditions it's possible to get a conclusion about which one of the scenarios is more profitable and eventually what is an optimal way to operate the battery.

The difference between the scenarios is related to the chosen operation hours. In All-scenario the battery operates in all possible FCR-N hourly market hours that Fingrid is willing to buy services and require at least 2 MW of capacity. In Hydro-scenario the battery functions in the same FCR-N hourly market hours when Fortum operates its hydroelectric power. Consequently, the main scope idea in All-scenario is that in the FCR-N hourly market the bid price for battery's 2 MW power capacity for each hour is sufficiently low so that it's accepted by Fingrid nearly every time. Moreover, in Hydro-scenario the battery is bid for the FCR-N hourly market according to the same mechanics as Fortum decides its optimal use of hydropower. Nonetheless, in both scenarios the Batcave battery is always operated primarily during every active hour while hydropower is used as a backup reserve. This means that if the battery can't operate depending on its full or empty state of charge hydropower is then used in order to deliver the agreed requirements for the grid. The two different scenario specifics are portrayed in Table 6.

Table 6: Different simulation scenarios.

	All-scenario	**Hydro-scenario**
Market:	*FCR-N hourly market*	*FCR-N hourly market*
Chosen operation hours:	*All hours that provide income and require at least 2 MW of power capacity*	*Hours when Fortum operates its hydroelectric power*
Primary operation:	*Batcave battery*	*Batcave battery*
Backup operation:	*Hydropower*	*Hydropower*

The Fingrid's FCR-N hourly market data of 2016 provides the precise hours when the battery would operate in the All-scenario (Fingrid, 2016s). Furthermore, for the Hydro-scenario Fortum's own hydro usage data was used in order to specify the required battery operation hours. These chosen hours are also referred as "filtered hours" and they provide the operation difference between the two simulation scenarios.

To summarize, from the frequency measurement data different operation hours are filtered according to the requirements of the two scenarios. This results in All-scenario and Hydro scenario frequency data which is then used in Batcave model that contains the actual calculation features and programmed functions. After running the Batcave model with the frequency data from both scenarios the operational results are achieved. The two simulation results in question can then be refined in profitability scenarios with the aid of FCR-N hourly market data and hydro data. FCR-N hourly data indicates the possible income for every hour that the battery is in operation during the year of 2016. If hydro power had to be used for power compensations, from hydro data, the cost of this operation was estimated with the hydroelectric water values (€/MWh) that are rough evaluations of the hydro energy prices for every hour. In the end, these profitability scenarios can lead into findings about how to optimize the use of Batcave battery. The roadmap of these simulations is illustrated in Figure 31.

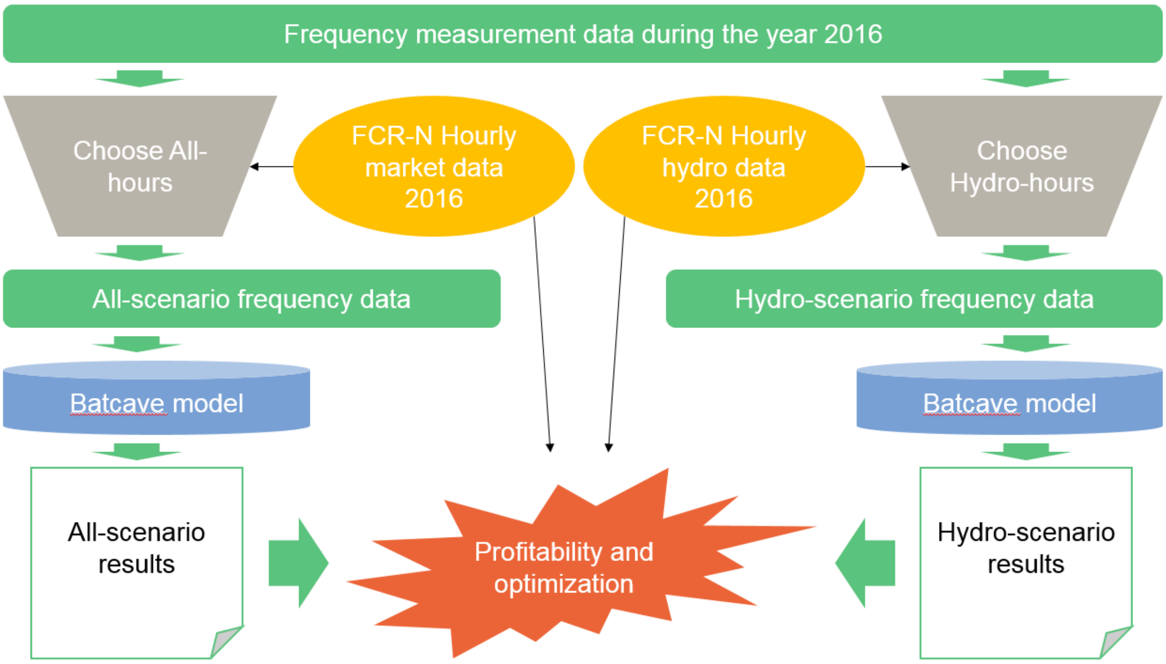


Figure 31: Roadmap of the simulations.

Beside the technical results of Batcave energy storage another perspective is also perceived during the simulations: virtual energy capacities. If the Batcave battery can't deliver the grid requirements, because it's either full or empty, hydropower is used as a backup reserve on those circumstances. Fortum's position on this matter is rather good since it owns sufficiently water power that can be used efficiently on the occasions in question. However, it would be important to understand what the approximate size of the battery's energy capacity should be in order that it could operate all alone in the FCR-N hourly market without any backup reserves. During these simulations the possible dimensions of autonomous batteries are referred as virtual energy capacities.

5.3 Batcave model

The purpose of Batcave model is that it reads the fed input frequency data and then simulates how the battery would actually operate during those grid requirements. After running the model in both scenarios, corresponding information can then be collected about its functions and assembled in respective scenario results. The Batcave model features two main aspects: the operation model and the used functions. The operation model defines how the battery performs under the influence of grid frequency variations and its requirements. Secondly, the used functions cover all the programmed formulas that will be calculated during the simulations.

5.3.1 Battery operation model

The battery operation is conducted according to the requirements imposed by Fingrid for the FCR-N market, which is described in more detail in Chapter 2.2.3.4. The market norms mean that the battery shall regulate nearly linearly between the frequency range of 49,90 – 50,10 Hz with a dead band of 50 $\pm$ 0,05 Hz. The maximum power of Batcave's 2 MW was applied in order to achieve justifiable operation functions for the model. The Equation of analytic geometry (10) was used to define the linear formulas of discharging and charging (Seppänen, et al., 2016):

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1}(x - x_1) \tag{10}$$

In this equation the variable y stands for the power output from the battery in megawatts (MW) and the variable x stands for the grid frequency (Hz). The model is done from the Batcave's point of perspective meaning that when the grid frequency drops the battery discharges itself. Consequently its inner energy capacity decreases in order to fulfill the grid requirements. The opposite charging operations are conducted when the grid frequency rises.

When x = [49,90; 49,95] the linear formula of discharging is defined as

$$y - (-2) = \frac{0-(-2)}{49{,}95-49{,}9}(x - 49{,}9) \tag{11}$$

$$y = 40x - 1998. \tag{12}$$

When x = [50,05; 50,10] the linear formula of charging is defined as

$$y - (0) = \frac{2-(0)}{50{,}1-50{,}05}(x - 50{,}05) \tag{13}$$

$$y = 40x - 2002. \tag{14}$$

With a dead band of x = [49,95; 50,05] the battery operation model is described in Table 7:

Table 7: Batcave control logic.

Power (MW)	Formula where [f] = Hz	Realize when f =	Operation
P =	-2	[−∞ ; 49,95]	Max discharge process
P =	40f - 1998	[49,90 ; 49,95]	Linear discharge process
P =	0	[49,95 ; 50,05]	Dead band
P =	40f - 2002	[50,05 ; 50,10]	Linear charge process
P =	2	[50,05 ; +∞]	Max charge process

The Batcave battery control logic is portrayed schematically in Figure 32. As it can be observed, Batcave battery operations implement the official FCR-N market requirements that are portrayed in Figure 12. With this control logic, accepted by Fingrid, the Batcave energy storage system started operating on March 1st 2017 in Finnish electricity market.

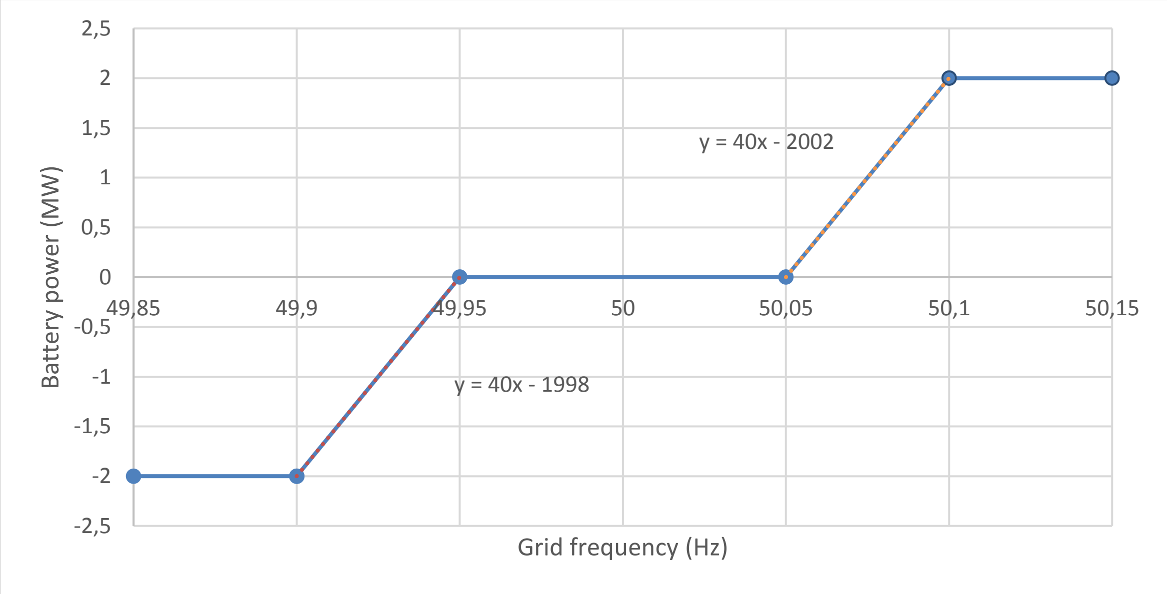


Figure 32: Batcave control logic from the battery's perspective.

The battery aging aspects are described in detail in chapter 4.4 and they have been applied for the Batcave model. In order for the battery to have the longest lifetime expectancy possible the whole energy capacity of 1 MWh won't be used. Nevertheless, to ensure functional operational possibilities the available energy capacity shouldn't be too strict. Thus, in the Batcave model its maximum reachable energy capacity is defined as 0,9 MWh and the minimum as 0,1 MWh so that calendar and cycle aging factors can be reduced sufficiently. This means that the energy capacity has 10 % buffers in its extreme boundaries resulting that the battery can only operate around SOC-levels of 10-90 %. Abbreviations of these limits in the Batcave model are known as *E_tot_max* and *E_tot_min*. The battery life expectancy according to the manufacturer has been applied for simulations when keeping the SOC-levels between 10-90 %.

5.3.2 Used functions

The used functions of Batcave model enable that the operation model performs as intended and that different information about simulation results can be gathered efficiently. In summary, the Batcave model includes specific formulas that are calculated during the scenario simulations. These formulas are divided into simulation functions and summary functions.

The simulation functions are calculated for every provided grid frequency point meaning that they are calculated for every second. In sum, the simulation functions support the battery operation model which was described in previous Chapter 5.3.1. Thus, simulation functions indicate the real time status and operations of Batcave battery. Alternatively, the summary functions are calculated separately for every day and generically they represent specific collection of that day's operations. In short, summary functions collect battery operation data for latter compilations and analyzations. The simulation functions are described in more detail in Table 8 and the summary functions are presented in Table 9. The formula specifications of simulation functions are described in Appendix 3 and summary functions in Appendix 4.

Table 8: Simulation functions for Batcave model.

Abbreviation	Unit	Simulation function (calculated every second)
P	MW	Indicates the battery's power output at given grid frequency. This leads either to negative discharging or positive charging of the battery or alternatively resting in its current state. The Batcave control logic from Table 7 is used in this formula.
E_in	MWh	Indicates the amount of energy that the battery is charged with.
E_out	MWh	Indicates the amount of energy that the battery is discharged with.
E_in_not	MWh	Indicates the amount of energy that the battery wasn't able to charge because it was already full.
E_out_not	MWh	Indicates the amount of energy that the battery wasn't able to discharge because it was already empty.
E_tot	MWh	Indicates how much energy the battery has inside.
SOC	%	Indicates the state of charge of the battery.
E_hypot.	MWh	Indicates how big energy capacity a hypothetical 2 MW battery should have in order that it never reaches full or empty state. In this function the hypothetical battery operates continuously with its own virtual energy capacity.
E_extra	MWh	Indicates how much extra energy capacity the Batcave battery should have in order that it never reaches full or empty state. In this function the extra batteries operate only when the Batcave cannot, leaving the primary energy adjustments for Batcave and secondary for extra batteries.

The summary functions form the basis for the simulation end-results. The outcomes from different summary functions are collected from every day and together they create the framework for final results. The summary functions are described in more detail on the table below.

Table 9: Summary functions of Batcave model.

Abbreviation	Unit	Summary function (calculated for each day)
E_in_sum	MWh	Summary of all the energy (*E_in*) that the battery has charged.
E_out_sum	MWh	Summary of all the energy (*E_out*) that the battery has discharged.
Active hours	h	Summary of the active hours that the battery has been operational.
E_tot_start	MWh	Starting energy level of battery which is identical to the last *E_tot* value when the battery was operational.
Cycle count	-	Summary of the consumed cycles.
E_in_not_sum	MWh	Summary of all the energy (*E_in_not*) that the battery wasn't able to charge because it was already full.
E_out_not_sum	MWh	Summary of all the energy (*E_out_not*) that the battery wasn't able to discharge because it was already empty.

First time full	h	The time spend for the battery to be for the first time full since the day's first activation.
First time empty	h	The time spend for the battery to be for the first time empty since the day's first activation.
Idle time full	h	Summary of time that the battery wasn't able to charge because it was already full.
Idle time empty	h	Summary of time that the battery wasn't able to charge because it was already full.
E_hypot. MAX	MWh	Indicates the uppermost value in the *E_hypot*. case.
E_hypot. MIN	MWh	Indicates the lowest value in the *E_hypot*. case.
E_extra MAX	MWh	Indicates the uppermost value in the *E_extra* case.
E_extra MIN	MWh	Indicates the lowest value in the *E_extra* case.
Last E_tot	MWh	Indicates the last *E_tot* value that remains from that day when the battery stopped operating.
Last E_hypot.	MWh	Indicates the last *E_hypot*. value that remains from that day when the battery stopped operating.
Last E_extra	MWh	Indicates the last *E_extra* value that remains from that day when the battery stopped operating.

5.3.3 Reliability of the model

Before executing scenario simulations the reliability of forthcoming results have to be evaluated and challenged accordingly. In this case, to compare the Batcave model to real battery functions, the real time reference data is used from official operational tests.

In order for a power generator to be able to provide its services for the power reserve markets its technical properties have to be formally and objectively tested. These official operational tests of Batcave battery were conducted on 8.2.2017. The results were reported for Fingrid in order to get the running license for operating battery in FCR-N market. The data from the tests is represented schematically in Figure 33.

In the FCR-N market, if the frequency drops to 49,9 Hz or below or alternatively rises to 50,1 Hz or over the power generator has to perform the maximum power service that it has offered for the market in question. During the authoritative tests the power producer's ability to carry out these requirements is evaluated.

During the tests the frequency data made two slopes, first with the frequency drop of 49,90 Hz and then a rise with 50,10 Hz, which is displayed graphically below the diagram with a scale on the right-hand side. The frequency shifts from 49,9 Hz to 50,1 Hz lead to maximum power demands that the battery has to endure. The obtained data measurement points are represented alongside the Batcave model results in order to properly compare the reliability of the simulations. The scale of the power outcomes are represented on the left side of the diagram.

The Batcave model, which is represented in Table 7 and in Figure 32, is applied in "upside down" results for Figure 33 and Table 10 so that the comparison material would be as explicit and as comparative as possible. This means that, contrary to the Batcave model, the discharging is presented with positive values and charging with negative ones. The difference results from the separate point of views: Batcave model is conducted from battery's perspective whereas the standard operation tests are performed from the grids standpoint.

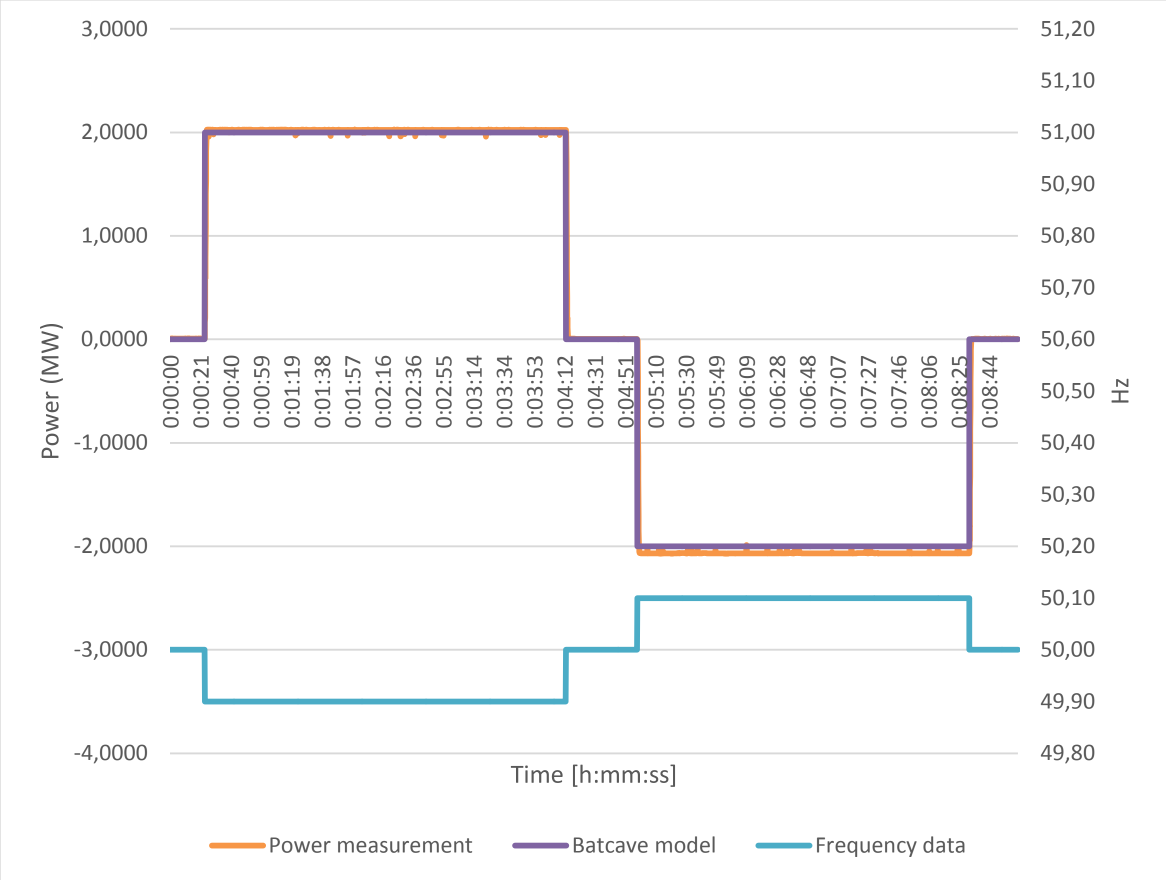


Figure 33: Comparison of Batcave model to the real time measurements.

Figure 33 shows that the model is well align with the actual measurement points. Real response time of the Batcave battery is short and thus it reacts fast to the frequency shifts. This respects nicely the simulation model in which an instant reaction to the frequency derivations is assumed in order to not complicate the model in excess. The measurement data shows micro variations around the power demands whereas the model conducts completely smooth outcomes. More precise differences between the measurements and model results are listed in Table 10. The column results of Real data average is calculated as the average of the measurement points after 1 second from the frequency shifts.

Table 10: Comparison of Batcave model to the real time measurements.

Frequency (Hz)	Real data average (MW)	Model results (MW)	Difference	Margin from Real
49,9	2,0230	2	0,023	1,1 %
50,1	-2,0667	-2	0,067	3,2 %

Table 10 represents that in the column of real data average the over-frequency results are slightly bigger than the ones of under-frequency. However, the difference is so minor that it doesn't present any practical relevance on the symmetry of the model. Additionally, the model results appear to be slightly smaller than measurement data points. In under-frequency situation the model indicates 1 % smaller results than in real operation and 3 % smaller outcome in over-frequency occasions. These margins of errors are in acceptable limits which indicate that the forthcoming simulation results can be considered as credible as well as applicable enough for the real world scenarios.

5.4 Simulation specifics

Simulation data began on the first day of January 2016 and operated during the whole year of 2016. In order for the battery to start operating as normally as possible it needed certain starting values that would determine its state of energy capacity (MWh) as well as the launch conditions of *E_hypot*. and *E_extra* cases. These default values are presented in Table 11 and they are chosen as the desired average statuses of the values.

Table 11: Starting values of the simulation.

Abbreviation	Unit	Starting value
E_tot	MWh	0,5
E_hypot.	MWh	0,5
E_extra	MWh	0,0

The simulation was first ran through the frequency data of All-scenario and then through the Hydro-scenario leading to comparable results. The simulations are done under the assumption of zero energy losses in order to not complicate the model excessively. Nevertheless, the efficiency of the battery is taken into account during the life expectancy evaluations and profitability calculations in Chapter 6.4 and Chapter 6.5.

Due to calendar aging and cycle aging the size of battery's energy capacity decreases as time goes by. However, in order to not have too complex relations in Batcave model the reducing factor of energy capacity is not taken into account during these simulations. Nonetheless, as the end-of-life state of battery is described as a fall of 30 % in its initial energy capacity the aging effect doesn't pose too radical impact on the simulation results.

The Batcave simulation is done under the presumption that all the functions of charging and discharging are performed only during the chosen active operation hours in the FCR-N market. Consequently, the battery's energy capacity remains in that exact state when it ends its operation and starts from that equivalent status when it begins to function again. This reduces the complexity of the simulation as no additional conditions have to be taken into consideration in which the battery would charge or discharge itself outside the operation hours. Additionally, this enables to survey how the Batcave could operate on its own in the FCR-N hourly market with hydropower as its backup reserve.

When the battery is either full or empty and it is unable to provide the agreed power capacity to Fingrid the reserve owner has to pay a compensation fee that is 100 % of that hour's price (Fingrid, 2017b). In order to prevent this high payment Fortum's hydroelectric power is applied to cover the necessary power requirements. This means that all the simulation functions of *E_in_not* and *E_out_not* as well as respectively their summary functions of *E_in_not_sum* and *E_out_not_sum* are carried out with hydro power. The compensation in question includes a presumption that because of huge energy capacities in water reservoirs the 2 MW of hydropower is available for those moments.

6 Simulation results and evaluations

After conducting the scenario simulations, the findings from All-scenario and Hydro-scenario were collected and concentrated on the same Windows Excel workbook for efficient comparisons. From both simulation scenarios the summary functions of Table 9 were gathered from every date during the year of 2016. The Fingrid's FCR-N hourly market data as well as Fortum's hydro data were also implemented on this workbook in order for the simulation results to be analyzed and quantified together. These findings will give conclusion about how the Batcave battery storage system would have been operating during the year 2016 and how the technical constraints would have been effecting it. Additionally, the needed sizes for autonomous virtual energy capacities are evaluated as well. The findings result in estimating the profitability of the Batcave scenarios and eventually in finding practices to optimize the battery operations.

6.1 Operational results

The operational results show how the battery would have been operating during the year 2016 and how the main differences between the two scenarios stand out. The operational results from simulations are listed in Table 12 and the summary functions in question are explained in detail in Table 9. In Table 12, the Abbreviation column points out the function names and the columns of All-scenario and Hydro-scenario show the result values according to Units column. The Difference column illustrates the difference between All-scenario and Hydro-scenario in same units. Additionally, Margin from All column shows how much the values of Hydro-scenario are smaller than the ones of All-scenario. If the percentage of Margin from All is negative it indicates how much the Hydro-scenario is bigger than the All-scenario. The margins are analyzed in more detail in Figure 36.

Table 12: Operational results from the simulations of the year 2016.

Abbreviation	Units	All-scenario	Hydro-scenario	Difference	Margin from All
E_in_sum	MWh	390	289	101	26 %
E_out_sum	MWh	-390	-289	101	26 %
E_sum	MWh	780	578	202	26 %
Cycle count		390	289	101	26 %
Lifespan	years	12,82	17,30	-4,48	-35 %
E_in_not	MWh	198	136	62	31 %
E_out_not	MWh	-215	-165	50	23 %
E_not_sum	MWh	413	301	112	27 %

Table 12 shows clearly that during the All-scenario the Batcave battery was operational more often than in Hydro-scenario. This stands to reason because the aim of the All-scenario was to make the battery operate during almost every possible FCR-N market hour whereas in the Hydro-scenario the chosen hours were more optimal and depended on the current power markets as well as on hydropower strategies. In comparison to operative hours, Figure 34 portrays the summary of energy flows from Table 12 that occur through the boundaries of Batcave battery.

In Figure 34 the abbreviation of *E_sum* includes the amount of energy that the battery has charged inside as well as the energy quantity of discharging outside. Additionally, the abbreviation of *E_not_sum* indicates the volume of energy that the battery wasn't able to charge or discharge because it was either full or empty. Consequently, *E_not_sum* represents the not-delivered total energy flow that occurs when the battery is in idling state.

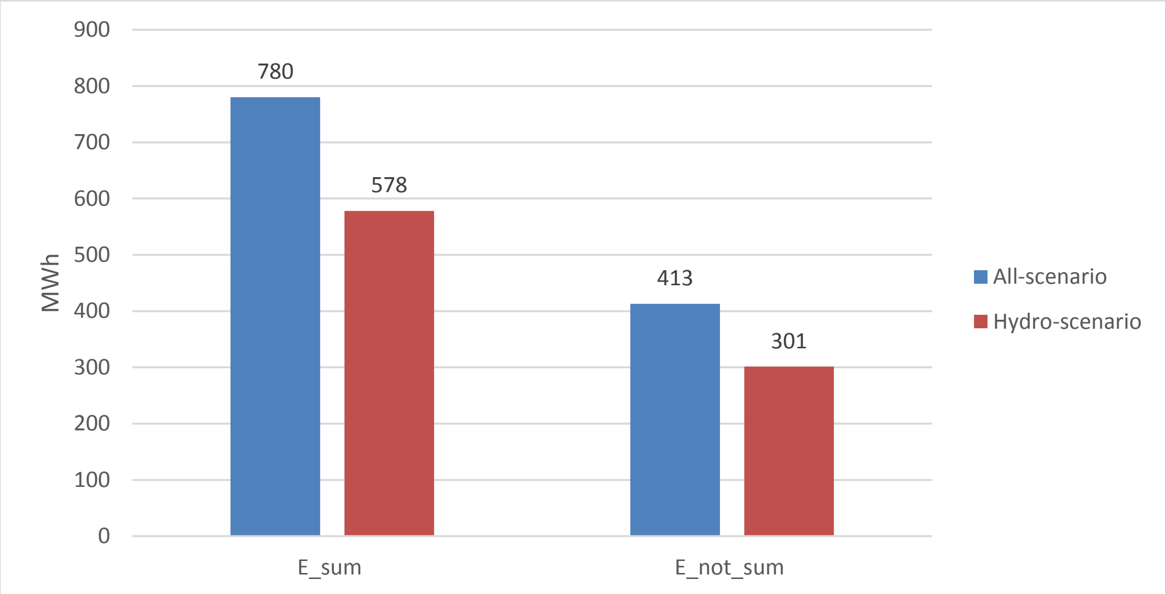


Figure 34: Energy flows from the simulations indicating the volume of operational and inoperative electricity transfers.

The chart of Figure 34 displays evidently that the values of both *E_sum* and *E_not_sum* are higher with the All-scenario than with Hydro-scenario. The outcome was yet predictable as the All-scenario had more active operation hours.

Table 13 represents different proportion statistics from the simulations that help to compare the operative indicators more clearly. The abbreviation of *Active hours* indicates the quantity of hours when Batcave was performing in the FCR-N market. Furthermore, the abbreviation of *Idle total* signifies the summary of time that the battery wasn't able to charge or discharge itself because it was already full or empty. The abbreviation column indicates the ratios of different functions that are expressed as percentage fractions in the next two columns. The division calculations show the proportions of not-able-to-operate functions to the entire quantities. The "total" relative functions of energy flows consist of the total sum of energy flows that the battery operated and should have been able to operate during the simulations. For example the *E_sum_total* is calculated as the sum of *E_sum* and *E_not_sum*.

Table 13: Proportion statistics from the simulations of the year 2016.

Abbreviation	All-scenario	Hydro-scenario
Idle full / Active hours	3,8 %	3,6 %
Idle empty / Active hours	4,6 %	4,7 %
Idle total / Active hours	8,4 %	8,4 %
E_in_not / E_in_total	33,6 %	32,0 %
E_out_not / E_out_total	35,6 %	36,3 %
E_not_sum / E_sum_total	34,6 %	34,3 %

It can be seen from the energy flow proportions of Table 13 that in both scenarios the battery is more frequently in situations where the energy capacity is empty and it isn't able to discharge electricity for the grid. In All-scenario the difference is more subtle than in Hydro-scenario where the chosen operation hours show relatively more under-frequency activity. Nevertheless, when considering the sum-function of *E_not_sum/E_sum_total* the percentage fractions of each scenario settle approximately on the same level. This shows that, in the long run, the limiting boundary of battery's 1 MWh energy capacity plays a more important role in operation ratios than the chosen active hours in these two simulations.

When it comes to operative hours and energy flows, the relations between battery activity and inoperative idling don't represent the same size ratios. Furthermore, to underline the difference between the temporal and energetic proportions from Table 13 the two total operation ratios are presented schematically in Figure 35.

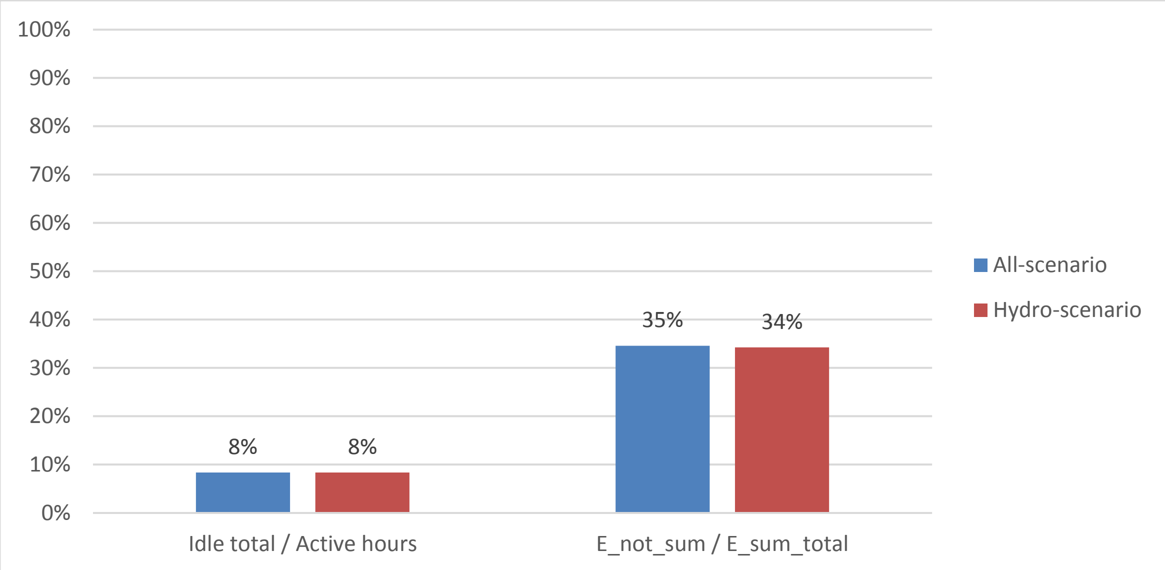


Figure 35: Operation ratios from the simulations indicating the inoperative share of battery operations compared to total activity and energy flow sums.

As it can be stated clearly from the Figure 35 that relatively the energy flow restrictions play a much bigger role in operation specifics than idling times. From all the active hours during the year 2016, only 8 % of that time the Batcave battery wasn't able to operate. However, this inoperative idling time consists of over one third of the total energy flow that the battery should have been able to deliver. Thus, it is reasonable to note that temporally the battery can surprisingly well operate alone in the FCR-N hourly market. Nevertheless, when idling occurs, the backup reserves that compensate the battery incapability have to provide sufficiently and instantly the required energy volume in that moment of need. Hydroelectricity can perform this task well although it adds additional uncertainties for the dam optimizations and operations.

Table 14 shows simulation statistics that are proportional in average for one day's time interval. This gives a relative idea about the Batcave's activity in a 24 hour period during the two simulations.

Table 14: Operational results from the simulations for daily statistics.

Abbreviation	Units	All-scenario	Hydro-scenario	Difference	Margin from All
E_in_sum	MWh/day	1,07	0,79	0,28	26 %
E_out_sum	MWh/day	-1,08	-0,79	0,28	26 %
E_sum	MWh/day	2,15	1,58	0,57	26 %
Cycle count	/day	1,07	0,79	0,28	26 %
E_in_not	MWh/day	0,54	0,37	0,17	32 %
E_out_not	MWh/day	-0,59	-0,45	0,14	24 %
E_not_sum	MWh/day	1,14	0,83	0,31	27 %

Figure 36 represents the chosen marginal percentages of Hydro-scenario from the All-scenario that can be found from Table 12. The margins indicate how much the values of Hydro-scenario are smaller than the ones of All-scenario.

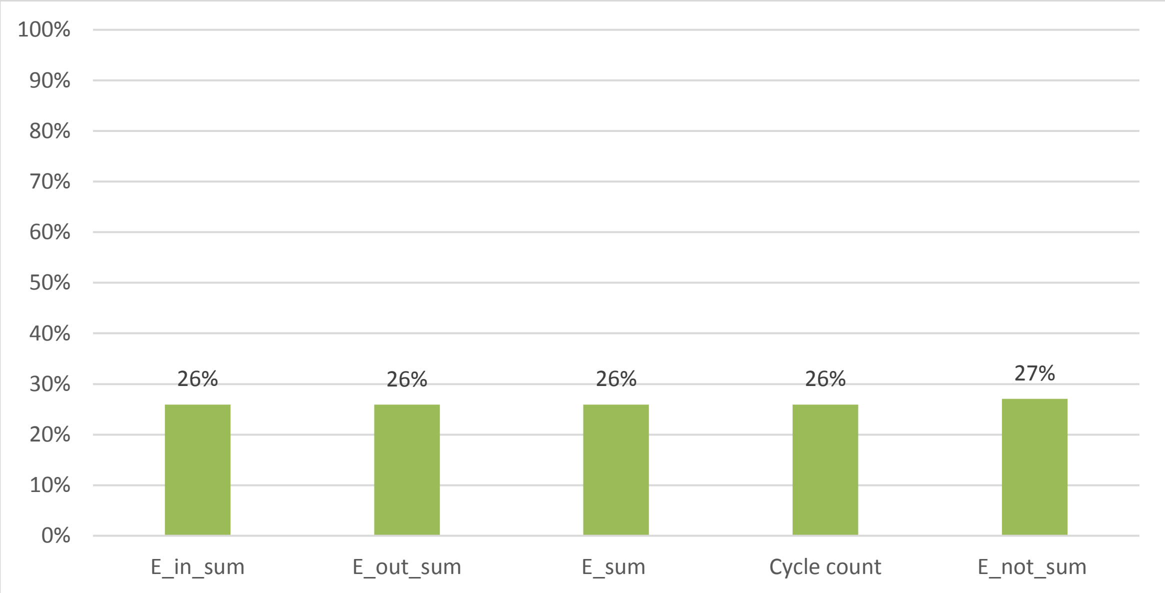


Figure 36: Margin of Hydro-scenario from All scenario indicating how much smaller the Hydro-scenario results are from All-scenario results.

As it can be stated from Figure 36 the different values of Hydro-scenario are around 26 % smaller than the ones of All-scenario. This shows that there is certain statistic linearity between the scenarios. This enforces the previous deduction with operation ratios that in the long run the chosen hours don't create huge operation differences between the two scenarios in the FCR-N hourly market. As the test sample is only with two scenarios no universal conclusions can be conducted from the margin similarity of Figure 36. However, this scenario linearity is exploited for reference value simplifications that are later on utilized in optimization evaluations of Chapter 6.5. It enables that by generalizing the observed linearity certain key ratios can be extrapolated in order to conduct the optimization calculations.

6.2 Virtual energy capacities

Alongside the operational simulations of Batcave battery two virtual energy capacities were calculated as well. The aim of simulating virtual energy capacities is to understand what the approximate size of the battery's energy capacity should be in order that it could operate all alone in the FCR-N hourly market without any backup reserves or optimizations. The virtual energy capacities are being referred as *E_hypot*. and *E_extra* and they are described at length in Table 8 and Table 9. Figure 37 shows graphically how the *E_hypot.* function operates in the All-scenario simulation during the year 2016. The data points show the required energy capacity size of *E_hypot*. at the beginning of every active hour that the battery is operational.

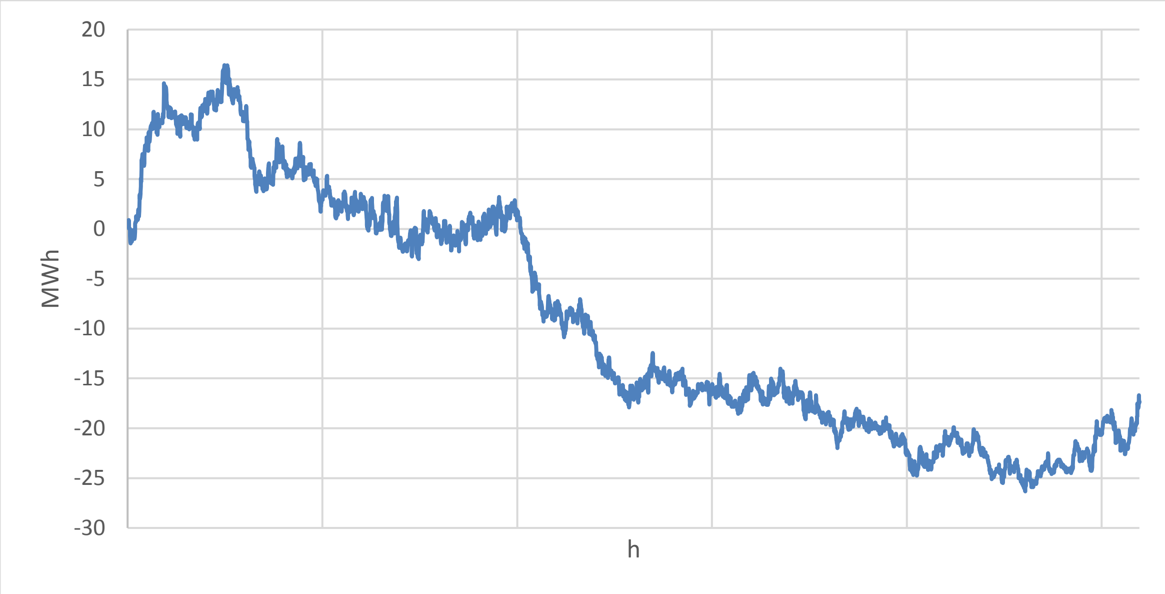


Figure 37: *E_hypot*. function values from the All-scenario simulations of the year 2016.

It can be stated from Figure 37 that during the early spring the grid frequency has more frequently an overvalue which leads logically the battery to charge itself. When the time goes by the grid suffers more and more about frequency undervalues during the chosen active hours which result in discharging of the battery. Thus, the virtual energy capacity of *E_hypot.* shifts from a positive pike of full-state battery into a negative bottom of empty condition during winter time.

Table 15 lists the results of Batcave's virtual energy capacities that are described at length in Table 8 and Table 9. The results of Table 15 are under the presumption that the virtual batteries operate at 100 % success rate in a way that hydroelectricity backup reserves won't get activated at any time.

Table 15: *E_hypot*. and *E_extra* statistics from the simulations of the year 2016.

Abbreviation	Units	All-scenario	Hydro-scenario	Difference	Margin from All
E_hypot. MAX	MWh	16,5	3,7	12,9	78 %
E_hypot. MIN	MWh	-26,3	-42,3	-15,9	-61 %
E_hypot. total	MWh	42,9	46,0	-3,1	-7 %
E_extra MAX	MWh	15,6	2,8	12,9	82 %
E_extra MIN	MWh	-26,4	-42,4	-15,9	-60 %
E_extra total	MWh	42,1	45,1	-3,1	-7 %

The statistics of Table 15 show that in both scenarios the maximum positive values are much smaller than the absolute minimum values. This indicates, as also seen from Figure 37, that during the year 2016 the chosen hours had more undervalues of frequency which resulted more often in discharging of the battery. Additionally, it is notable that the Hydro-scenario has smaller maximum values but instead higher minimum values. This is because the Hydro-scenario has less operation hours during the spring when the grid has more overvalues of frequency which leads, in the long run, to the dominance of undervalues. The total virtual energy capacities are represented graphically in Figure 38 where the real Batcave battery size is also implemented alongside the columns in order to visually comprehend the dimension differences.

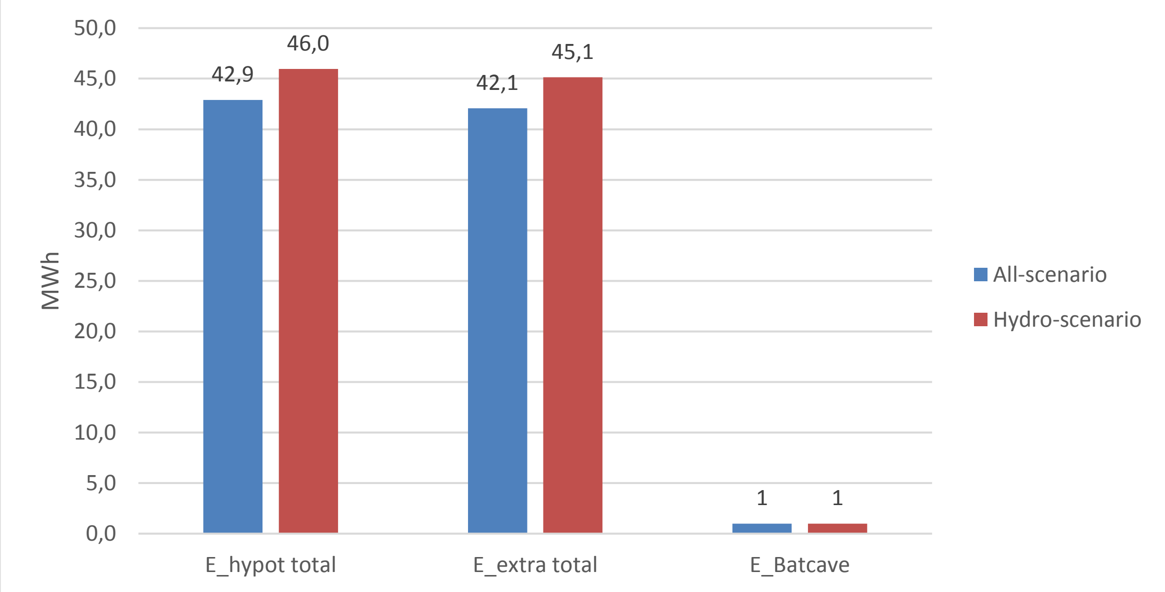


Figure 38: Virtual energy capacities from the simulations indicating the needed battery sizes that the virtual batteries could operate all alone in the FCR-N hourly market without any backup reserves or optimizations at 100 % success rate. Batcave energy capacity size is added for comparison.

These findings lead into two different battery operation aspects. From Table 13 and Figure 35 it was noted that the limiting boundary of battery's 1 MWh energy capacity has a more important role for operation ratios than the chosen active hours in the scenarios. The findings from the two simulations show that there is certain linearity between different results. The strict energy capacity limits lead to similar simulation situations where the full or empty battery conditions restrict efficiently the operation possibilities during a long lasting grid frequency shift.

Nevertheless, Figure 38 represents that when inspecting the virtual energy capacity boundaries the results are anything but linear in proportion. In both functions of *E_hypot. total* and *E_extra total* the Hydro-scenario needed bigger energy capacity than the All-scenario although it had fewer operation hours. Thus, in these scenarios fewer active hours resulted in missing certain significant hours that had an effect in overall stabilization of virtual energy capacity. This points out that when determining virtual energy capacities where no backup reserves would be used, the chosen scenario hours have an important impact on the outcome. Consequently, this means that there is a huge uncertainty factor of batteries regarding the hourly frequency variations if they need to function independently with a 100 % success rate. Therefore, the cost of such big energy capacities is too substantial in order to reach, in an economic manner, a completely autonomic battery with no backup reserves or optimizations and always carrying out the grid requirements.

The starting values of the simulations that were listed in Table 11 determined the beginning SOC-values for both virtual energy capacities. The maximum and minimum energy capacities of Table 15 determined the full-state and empty-state boundaries and the starting values defined at what level the battery was charged with when the simulations started. These *SOC-start* results are represented in Table 16.

Table 16: SOC-values on virtual energy capacities.

Abbreviation	All-scenario	Hydro-scenario
E_hypot. SOC-start	61 %	92 %
E_extra SOC-start	63 %	94 %

Table 16 shows that the Hydro-scenario needed a much higher *SOC-start* level than All-scenario. This arises from the fact that the Hydro-scenario has less operation hours during the spring when the highest positive peak would have been achieved. Thus, the Hydro-scenario needs a significantly higher SOC-level in order to manage the forthcoming discharging periods. The notable differences between the SOC-levels signify that the required virtual energy capacities of Table 15 and Figure 38 would be in reality much bigger. The simulations assume that the correct SOC-level would have been planned correctly at the beginning of the year but in reality it would be extremely difficult to forecast the incoming frequency shifts during the future active hours. In other words, to minimize the uncertainty in which level of *SOC-start* should be an extra buffer in full-state and empty-state boundaries of virtual energy capacities would be required. This indicates that in reality the virtual energy capacities should be substantially bigger than the results suggest. Nevertheless, if a battery storage system is designed to work all alone in FCR-N hourly markets it should have more sophisticated optimization tools to charge and discharge the battery outside the active hours with certain price levels. Consequently, if optimal planning is included for the battery operations the virtual energy capacities could have smaller sizes.

6.3 Profitability of scenarios

In addition to the operational results and virtual energy capacity estimations from the simulations, the financial aspects of Batcave battery were evaluated as well. The profitability results indicate the monetary value that the battery system could provide inside the scope of chosen scenarios from the year 2016. With Fingrid's FCR-N hourly market data of 2016 it's possible to compare All-scenario and Hydro-scenario with an economical perspective.

The cash flow results from the simulations are represented graphically in Figure 39. The *Profit* is calculated by reducing the idling cost from the total income values. The idling cost means the financial impact of using Fortum's hydropower to compensate the idling times of Batcave. Thus, when Batacve is full and charging is required or empty and discharging is required the backup reserve of water power is used in those situations. The idling cost is calculated with using the water value estimates that Fortum has evaluated for its reservoirs for every hour during the year 2016. Water value is explained in more detail in chapter 2.3.2. The hydro data in question is used for those hours when the battery idling occurs. Because of the uncertainty factor that is related to the idling cost, the yearly profit results of Figure 39 are represented in range of variations. The values of axes in Figure 39 are not shown for confidentiality reasons. Nevertheless, the scale in *Profit*-axis is identical in All-scenario and Hydro-scenario in such a way that they both start from zero value. The identical scales of Figure 39 indicate that the charts are entirely comparable.

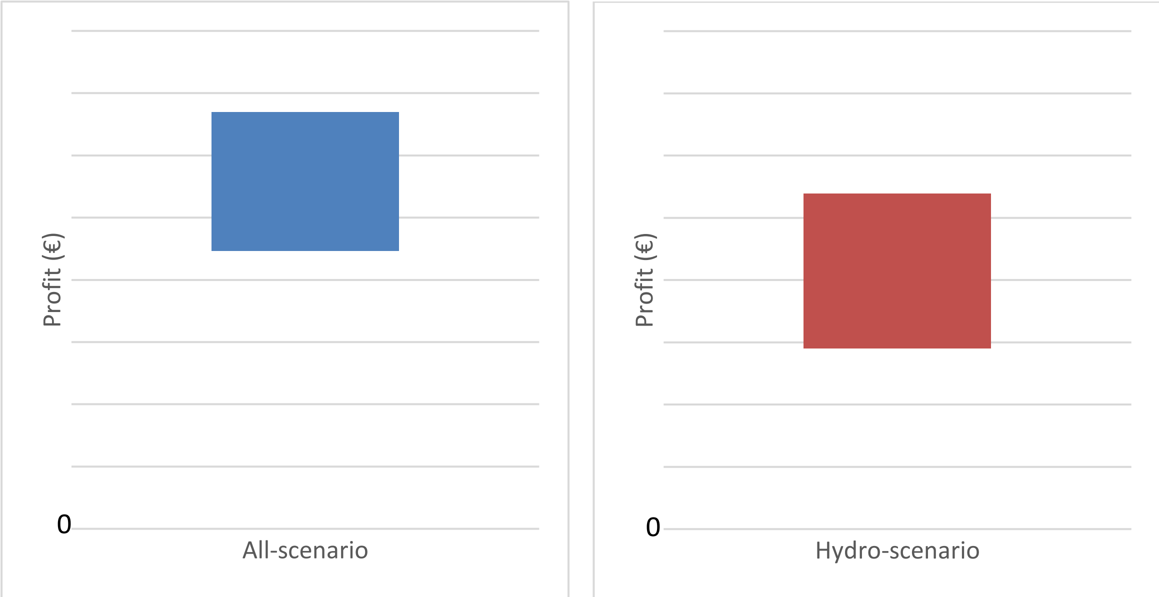


Figure 39: Cash flow statistics from the simulations.

As it can be estimated Figure 39 All-scenario provides bigger income than Hydro-scenario. This seems natural as in All-scenario the battery was operational more often and thus receiving more earnings. Both scenarios offer relatively acceptable profits above zero and thus the use of hydropower to compensate the battery idling times doesn't pose too radical effects on the total battery profit scenarios from the simulations.

Yet, it has to be noted that when hydropower is used in idling situations the water power has to be consumed no matter the hydropower plant operation plans. However, because of the proportionally small volume of used water, the effect of hydro operation demand can estimated to be relatively small and thus it hasn't been taken into account.

6.4 Net Present Value of scenarios

The simulations presented what the profitability prospects were after operating in the FCR-N market during the year 2016. However, in order to get a general scope about the profitability of the whole project the calculations of net present value (NPV) had to be conducted.

Because of the time value of money, time has an impact on value of cash flows meaning that the same amount of money is worth more during the present than in the future. The discount rate element of the NPV formula takes into account the uncertainty and monetary inflation. For net present value, the present value (PV) of costs and incomes are calculated for each period of an investment. Thus, NPV is defined as the sum of all the discounted future cash flows which indicates whether a project will end in a net profit or loss. If the NPV has an positive value the project will end in profit while a negative result signifies a loss. (Gallo, 2014) The NPV formula is represented in Equation (15) .

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{15}$$

where t Number of time periods
r Discount rate
C_t Net cash flow (€)
C_0 Initial investment (€).

The Finnish Ministry of Employment and the Economy (TEM) has granted financial support of 30 % for the total investment costs of the project (Fortum, 2016). This financial subsidy is known as TEM in this thesis while referring to the attained 30 % investment aid. The total investment costs comprise of battery and inverter costs, expenses of electrical, automation, civil and consultant works as well as in-house commitments. These investment expanses are also known as capital expenditures (CAPEX). The final costs of the Batcave project are listed in Table 17 with or without the TEM subsidy.

Table 17: Total investment costs of Batcave project.

CAPEX	Without TEM	With TEM
Total investment cost	- 1 600 000 €	- 1 120 000 €

After the investment, in order to keep the Batcave battery operational around the year in an optimal manner, certain costs will occur. These operating expenses (OPEX) arise from the continual costs Fortum has to pay to run the battery's basic business. The annual operating costs and their explanations are listed in Table 18.

Table 18: Operational costs of Batcave and their explanations.

Operational costs	Explanation
Energy compensation and imbalance costs	The energy compensation of discharging and charging the battery according to Fingrid's agreement (Fingrid, 2016p). With imbalance power the customer balances the difference between electricity acquisition and supply (Fingrid, 2017f).
Trading and development	In-house costs to plan the battery operation in reserve markets and the development hours to enhance the process as well as battery optimization.
O&M in site	The operation and maintenance cost that occur in the site. The value is an yearly estimate based on real tenders proposed by service companies.
Transmission costs and corresponding taxes	Caruna Oy works as the regional network company that provides the electrical transmission services for the battery site. These costs are calculated on how much the battery would have been paying fees and taxes in 2016 for Caruna.
Electrical losses and auxiliary power	The electricity losses are based on the efficiency of the battery. The auxiliary power costs consist of the electricity consumption needed for air conditioning, heating and maintaining the communication systems. The average Elspot-price of 32,45 €/MWh from the year 2016 was used, data from: (Nord Pool, 2017).

Uncertainty buffer	The uncertainty buffer is an extra cost to cover the unexpected incidents or realized risks. It's an estimated percentage of the sum of the other costs

When counting the net present value for the scenarios, in order to have simplified calculations, it's assumed that the year 2016 will be repeated annually. This signifies that the bidding and participating for the FCR-N hourly market will be conducted similarly every year for both scenarios with the same incomes and operational costs. Thus, it's expected in this presumption that the FCR-N hourly market stays the same, neither increases nor gets saturation effects.

Consequently, after reducing the operating expenses from the incomes of year 2016 the annual profit values can be calculated. The expected yearly income of Batcave battery is presented in Table 19 which is acquired from Chapter 6.3. From those values the OPEX estimates of Table 17 are subtracted. Additionally, because of the electrical losses the battery functions slightly more than the simulation results indicate with zero energy loss presumptions. Consequently, the cycle aging is slightly more active than the simulations suggest and thus the life expectancies of scenarios are multiplied with battery efficiency of 95 % in order to get more realistic results.

Table 19: Yearly profit before OPEX-subtract and life expectancies for NPV calculations.

	All-scenario	**Hydro-scenario**
Yearly profit before OPEX-subtract (€)	Left chart from Figure 39	Right chart from Figure 39
Evaluated life expectancy	12,2 years	16,4 years

Table 20 represents NPV results of All-scenario at the end of its life expectancy and Table 21 represents the NPV results of Hydro-scenario at the end of its life expectancy. The rounded down life expectancy values, used in NPV calculations, are also listed in Table 20 and Table 21. The NPV calculations are conducted with Equation (15). Because of the uncertainty factors the results of Table 20 and Table 21 are represented in range of variations.

Table 20: NPV results of All-scenario at the end of life expectancy.

Life expectancy (years)	**Without TEM NPV range of variation (€)**	**With TEM NPV range of variation (€)**
12	[-590 743 ; -213 939]	[-110 743 ; 266 060]

Table 21: NPV results of Hydro-scenario at the end of life expectancy.

Life expectancy (years)	**Without TEM NPV range of variation (€)**	**With TEM NPV range of variation (€)**
16	[-1 048 655 ; -606 087]	[-568 655 ; -126 087]

Figure 40 portrays the results of Table 20 in a diagram and Figure 41 portrays the results of Table 21 in a diagram. The diagrams are regrouped together in order to facilitate their comparisons.

Figure 40: NPV results of All-scenario at the end of life expectancy.

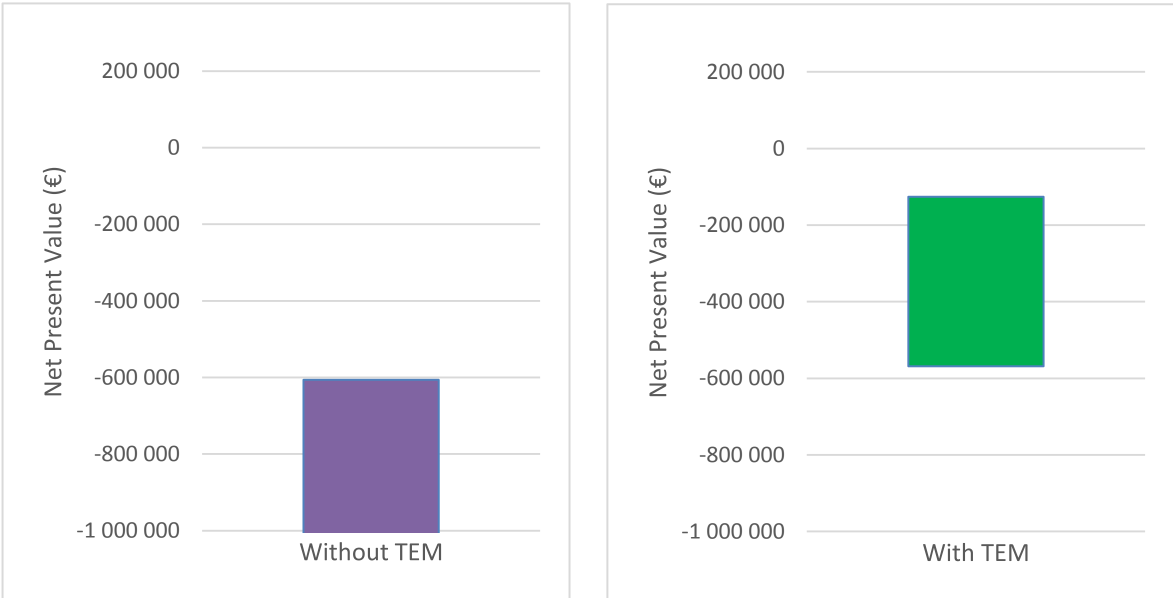


Figure 41: NPV results of Hydro-scenario at the end of life expectancy.

As it can be seen from Table 20, Table 21, Figure 40 and Figure 41 the range of variation size between *Without TEM NPV* and *With TEM NPV* is identical for two scenarios because the only difference is the starting investment costs. Furthermore, it's notable that the All-scenario reaches better net present values at end of the project life than Hydro-scenario. This signifies that although the Hydro-scenario has better life expectancy with fewer operational hours, the discount rate effect to the cash flows has a huge impact for the NPV values. From the financial aspect this occurs in such a way that the profits from final years' operations lose their monetary effect in relation to the original investment costs. Consequently, the NPV calculations from the simulation scenarios show that it's more profitable to operate the battery in almost every FCR-N hourly market slot possible than spare it's use only in conjunction with hydropower. This is also an acceptable conclusion from the viewpoint on minimize the uncertainty risks of possibly changing FCR-N markets and controlling the external effect that the battery systems become cheaper in the future.

Table 20, Table 21, Figure 40 and Figure 41 show that in order for the Batcave battery to be profitable enough in All-scenario the TEM subsidy is obligatory. Because the Batcave battery storage system functions as a research and development project the financial support of TEM was the only possibility of being able to study battery operations in reserve markets in the first place. Consequently, with the high investment costs and moderate incomes from the year 2016 a battery system won't offer profitability prospects without any investment subsidies. However, there is a global trend that confirms that the battery prices will decline greatly by the following years (Nykvist & Måns, 2015). Thus, in the future with decreased investment costs a battery systems can be moderately profitable in the Finnish reserve markets even without any state subsidies. However, because of the relative small size of Finnish FCR-N hourly market, the cannibalization could cause severe saturation effects for profits of possible future battery projects.

Table 20, Table 21, Figure 40 and Figure 41 indicate that in All-scenario and with TEM subsidy the payback time of Batcave can be expected to occur before the battery reaches its end-of-life state. Moreover, after the lifespan of battery system the final NPV value of All scenario signifies a moderately lucrative project on the whole with the TEM subsidy. This shows good result as the market data from the year 2016 represented the worst possible year from the FCR-N hourly market perspective between the years 2011 and 2016. As seen in Chapter 2.3.2 the average price of 2016 was exceptionally low which has an evident negative effect for the previous NPV calculations as it's specifically the year 2016 that was expected to be repeated. Because the FCR-N hourly market prices have already improved for the year 2017 the payback time and the final NPV values of Batcave battery can be approximated to be slightly better as long as the markets won't suffer from strong saturation effect.

6.5 Optimal operations

The simulation results showed how the Batcave battery would be operational during the two different scenarios and what those profitability prospects would be. Nevertheless, because All-scenario and Hydro-scenario included hours that were filtered depending on the wanted scope characteristics they don't necessarily indicate the optimal way to operate the battery. As noticed from Chapter 6.4, All-scenario creates more profitable business case but since it also includes low-paying hours it's worth studying the most optimized ways to operate the battery. Moreover, better battery operation plans are needed for the FCR-N hourly market.

The optimal operation of Batcave signifies that at what minimum hourly price the power capacity should be sold in order to maximize the profits. Because conducting the model simulations throughout the data from 2016 with all the different price scenarios takes a lot of time, certain assumptions are made so that the calculations could be simplified. Because of the simulation scenario linearity, that was noticed in Figure 36, there is certain margin similarity between the scenarios. Thus, this enables that by generalizing the observed linearity certain key default ratios can be extrapolated.

For the optimization calculations one key default ratio of *Aging per hour* was estimated as presented in Table 22. This key default ratio was evaluated from the simulation results of

All-scenario and Hydro-scenario. Fortunately, the original results from scenarios resulted in ratios that had relatively close values so it was possible to apply realistic approximation. The similarity between key default ratios can be observed in Table 22 where the margin between scenario results have been represented. *Aging per hour* ratios were quite close to each other which resulted in relatively small margin value.

Table 22: Key default ratio for optimization calculations and its margin between scenario ratios from simulation.

Key default ratios	**Margin between scenario ratios from simulation**
Aging per hour	0,24 %

For the optimization calculations the FCR-N hourly market data from 2016 is used. In this data the used hours and gained profits are filtered and then calculated depending on the hourly prices. First, the hour counts and incomes are calculated if the battery is operational for every hour. Then, the same calculations are conducted whether the battery is operational during the hours that offer 1 €/MW or more for the capacity. After, the hours that offer the 2 €/MW limit or more for the capacity. Next, a minimum of 3 €/MW and so on until a series of data is obtained about the price limit demands for battery operations that include the required active hours as well as its income prospects. Furthermore, the idling cost of hydropower was estimated for yearly cash flows of each price limit. As also used in previous NPV calculations, the life expectancies of scenarios are multiplied with battery efficiency of 95 % in order to get more realistic lifespan results. Lastly, the net present value calculations of Equation (15) are conducted for these price series while using information from Chapter 6.4, especially CAPEX values and OPEX estimates, in addition to aging ratio from Table 22. Consequently, it was possible to calculate the life expectancy and the final NPV results for each price limit. These optimization results are presented graphically in Figure 42. The values of axes in Figure 42 are not shown for confidentiality reasons.

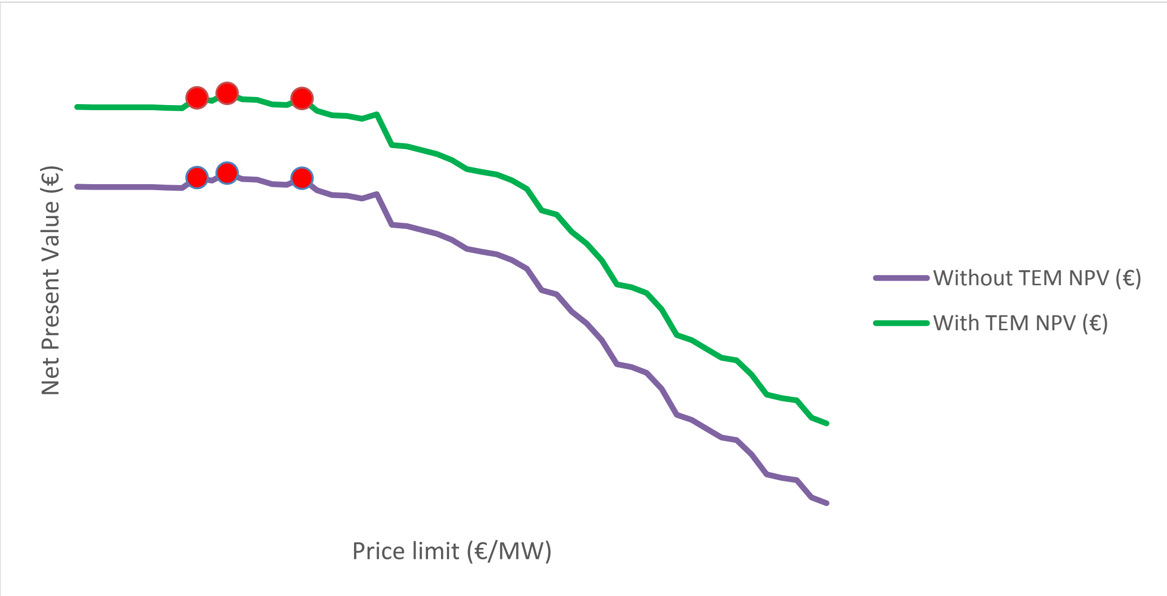


Figure 42: NPV diagram of Batcave operation with different price limits.

As it can be seen from Figure 42 there is clearly certain price limits when the operation of Batcave battery is the most profitable. The curves between *Without TEM NPV* and *With TEM NPV* behave identically because the only difference is the starting investment costs which lead to the observable shift in NPV-axis. The three biggest NPV spikes are marked with red dots. From these pikes the middle one represents the most profitable scenario and after the third spike the NPV values start to decrease dramatically. Generally, the most profitable scenarios can be found inside the interval of first and third spike.

Consequently, because of the uncertainty of market evolution, it won't be sensible to bid Batcave battery capacity only for FCR-N hourly markets with the price limit of second spike although it represents the most profitable scenario. Instead, the optimal price limit scope between the first and third spike should be applied accordingly. This gives enough liberty and option to optimize Batcave battery use depending on the current market developments and available production portfolios. Naturally, it has to be noted that these results are based only on simplified simulation calculations and they don't represent any real power trading guidelines or suggestions.

6.6 Assessment of results

All the results were conducted from simulations that were based on Fingrid's source data and applied on Batcave model. As the simulations are always a representation of real word functions their results have to be evaluated with certain objectivity.

The official frequency measurement data was registered every one hundredth of a second. The data contained some minor gaps because of the telecommunication errors yet they didn't occur too often to have any larger impact on simulation results. Furthermore, the data points were filtered to show frequency measurements for every second which left the data precision however accurate enough in order to operate reliable simulations.

When the Batcave model was compared to the real time measurements the model results appeared to be slightly smaller than the measurement data points as seen in Table 10. These margins of errors are in acceptable limits which indicate that the simulation results can be considered as credible as well as applicable enough for the real world scenarios.

The simulations were conducted under the assumption of zero energy losses which gives slightly better outcomes for operational results than would be expected in real life. However, because the efficiency was estimated to be around 95 % its effect doesn't create too much distortion for results. Moreover, the efficiency of the battery was taken into account during the life expectancy evaluations and profitability calculations in Chapter 6.4 and Chapter 6.5. This enables to achieve more realistic life expectancy values with influence of repetitive efficiency losses.

Due to calendar aging and cycle aging the size of battery's energy capacity decreases as time goes by. However, in order to not have too complex relations in Batcave model the reducing factor of energy capacity is not taken into account during these simulations. Since the energy capacity decreases as time goes by, the share of idling will grow respectively. Due to increase in paying for hydropower compensations the yearly incomes would get smaller as time goes by which would consequently decrease the NPV results. Nonetheless, as the end-of-life state of battery means that the energy capacity falls to 30 % from its initial size, the inoperative share isn't yet too radical. Moreover, the battery could still be operated after its life expectancy if wanted and resulting in better project profitability prospects.

In the NPV evaluations, although the OPEX values of Table 18 were calculated accurately, there are always uncertainties related to monetary valuations. Thus, an uncertainty buffer was implemented for NPV calculations in order to mitigate risks of operational cost. Nevertheless, the biggest uncertainties with NPV calculations and optimizations are related to the market size and price developments. Because the market share of power capacity in Finnish FCR-N hourly market is relatively small a large-scale "battery rush" on that market could cause some saturation effects. As the market sizes and prices are expected to stay at the same level in conducted NPV calculations, significant changes in energy infrastructure would have major impacts on the NPV and optimization results. Consequently, because of the uncertainty of the future, the conducted NPV calculation outcomes and optimization results should be rather considered as a scope of evaluations for battery project profitability.

In the future in order to ameliorate the reliability of simulations, the energy efficiency of battery storage system should be included directly to the simulation functions. Additionally, the aging effect of the energy capacity is worth adding to the NPV calculations and optimizations. Nevertheless, the most important aspect of the battery model is to develop the simulation functions as realistic as possible according to real measurements data that can be now acquired from Batcave battery operations.

Moreover, when the Batcave battery approaches its end-of-life status, economic examinations should be conducted about its future service possibilities. Because the basic transmission infrastructure is already built for the battery storage system, an exchange of used lithium ion cells for new units could provide financially an interesting maintenance possibility.

At present, the Batcave battery charges and discharges itself only during the chosen active hours in the FCR-N hourly market. However, in the future it would be useful to develop algorithms to find when and at what price levels the battery should charge or discharge itself outside the active hours. The economic calculations should be conducted about the benefits of having the battery approximately in the upper-middle of the SOC-level before starting new operations, at the expense of paying transfer costs. These results could help to design functional solutions for reinforcing stand-alone possibilities of batteries. Consequently, better self-reliant batteries could be designed to operate without any backup reserves. Thus, the battery markets could be planned to extend outside the scope of Finnish power system and possibly create more decentralized battery solutions for customers.

The Batcave model was originally conducted for Finnish FCR-N market with the Batcave battery storage system specifications. However, the model could also be utilized for primary market inspections in other countries with any wanted battery characteristics. As long as there are sufficiently grid frequency data points and the market requirements are known precisely, it's possible to simulate the same results as were calculated for Batcave battery. This enables that the simulations can be conducted for different battery specifications of power and energy capacity, in which case it's possible find optimal battery sizes and best business cases for different markets.

7 Conclusions

A 2 MW and 1 MWh battery energy storage project called "Batcave" started operating in Finland on March 1st 2017. The purpose of this thesis is to simulate how the Batcave battery storage system in question would operate in Finnish electricity reserve markets with the support of hydropower. This contains viewpoints about battery's technical characteristics and how they assist or constrain the operation possibilities. Additionally, the size of a stand-alone battery system is evaluated in order to get perspective about the influence of a hydro backup reserve. Moreover, the profitability opportunities of Batcave are studied, and further, the outcomes help in reviewing the optimal practices to operate the battery storage system.

7.1 Lithium ion batteries in FCR-N hourly market

First of all, from different available electricity market places in Finland the most suitable market had to be chosen for battery operations. Because in Nord Pool physical markets the price volatility and arbitrage aren't sufficiently big enough at the moment, a battery system doesn't appear to be economically viable in charging with low price and discharging with higher price. Moreover, as huge energy volume transmissions are normally required in this market, the limited size of energy capacities set clear restrictions for batteries to be functional enough. Contrary to physical markets, Batcave suits well in the Finnish electricity reserve markets since battery technology enables short activation times, effective reactions for frequency variations and good efficiency ratios. From available reserve market places, the FCR-N hourly market, that has the strictest operation requirements, takes into account the best characteristic of battery technology and offers currently the most profitable prospects for large-scale battery projects.

The battery types that have enough mature technology and suitable usability for energy storage systems applications are considered as lead acid battery, sodium sulfur battery, lithium ion battery, metal air battery and flow battery. From these types the Li ion batteries show the most promising potential for future development as well as optimization. Li ion batteries are light with the highest energy density and great storage efficiency. However, they are still expensive because of the complex manufacturing process of protection circuitry although their prices have decreased significantly during recent years. Since the lithium ion technology has currently a domineering status in energy storage applications, a lithium ion battery was also chosen for the Batcave project as well as for the majority of all the other battery storage projects in the world.

7.2 Conclusions from Batcave simulations

In order to find the best operation possibilities and the most profitable cases for the Batcave battery, two different simulation scenarios were conducted for the FCR-N hourly market: in All-scenario nearly all the hours with income were chosen whether in Hydro-scenario the hours with hydropower implementation were used. The simulations were ran with a designed Batcave model to estimate how the battery would have been operational during the year 2016 and what its profitability prospects would be.

To sum up the operational results from the simulations, relatively the energy flow restrictions play a much bigger role in operation specifics than idling times. From all the active hours, only 8 % of that time the Batcave battery wasn't able to operate whereas it included over one third of the total energy flow that the battery should have been able to deliver. Thus, it is reasonable to note that temporally the battery can surprisingly well operate alone in the FCR-N hourly market. Nevertheless, when idling occurs, the backing up reserves that compensate the battery incapability have to provide sufficiently and instantly the required energy volume in that moment of need. Hydroelectricity can perform this task nicely in a technical manner.

Alongside the operational simulations, virtual energy capacities were calculated as well. The aim is to understand what the approximate size of the battery's energy capacity should be in order that it could operate all alone in the FCR-N hourly market without any backup reserves or optimizations at 100 % success rate. The results show that the energy capacities should be over 42 - 46 times bigger than currently in Batcave. Moreover, the sizes should be in reality much bigger as there is a huge uncertainty factor of battery operations regarding the hourly frequency variations. Therefore, the cost of such big energy capacities is too substantial in order to reach, in an economic manner, a completely autonomic battery with no backup reserves or additional optimizations and always carrying out the grid requirements.

When it comes to simulation profitability, All-scenario provides bigger income prospects from the year 2016 than Hydro-scenario which seems natural as in All-scenario the battery is operational more often. From the NPV calculations throughout the battery life expectancy, it can be stated that All-scenario has better profitability prospects at end of the project life than Hydro-scenario. This signifies that although Hydro-scenario has better life expectancy with fewer operational hours, the discount rate effect to the cash flows has a huge impact at the NPV values. Consequently, the NPV calculations from the simulation scenarios show that it's more profitable to operate the battery almost as much as possible to assure quick cash flow than spare its use only in conjunction with hydropower. This is also an acceptable conclusion from the viewpoint on minimize the uncertainty risks of possibly changing FCR-N markets and controlling the external effect that the battery systems become cheaper in the future.

The results from NPV calculations show that in order for the Batcave battery to profitable in All-scenario the TEM subsidy is necessary. Because the Batcave battery storage system functions as a research and development project the financial support of TEM was the only possibility of being able to study battery operations in reserve markets in the first place. The NPV calculation results indicate also that in All-scenario and with TEM subsidy the payback time of Batcave can be expected occur before the battery reaches its end-of-life state. Moreover, after reaching the end of lifespan, the final NPV range of variation of All-scenario is mostly positive which signifies a moderately lucrative project on the whole.

The optimization calculations indicate that the minimum price limit of bidding the Batcave battery in the FCR-N hourly market has a clear scope interval with first and third spike values while aiming at the second spike area. This gives enough liberty and option to optimize Batcave battery use depending on the current market developments and available production portfolios. Naturally, it has to be noted that these results are based only on simulation calculations and they don't represent any real power trading guidelines or suggestions.

On the whole, the Batcave battery with 2 MW power output and 1 MWh of energy capacity manages fairly well in the FCR-N hourly market as a concentrated grid storing solution. The inoperative times don't occur that often and hydropower functions efficiently as an backup reserve for those occasions in question. With TEM subsidy the profitability prospects for Batcave are positive when the most optimized ways to operate the battery are applied. The Batcave battery storage system demands now systematic operation and active data analyzing for enhancing the technical specifications as well as to adjust for future alterations in reserve markets. Furthermore, it's important to examine how different operation styles wear the battery system and how the Batcave aging is developing compared to the simulation results.

Since the battery costs keep decreasing and customers become more and more interested in installing their own decentralized electricity storing units, the batteries' final role in future energy infrastructure cannot be consider as predetermined. Nevertheless, whether the future brings concentrated or decentralized battery storage systems or, as more likely, a combination of them, it's generally agreed that more economically viable electricity storing applications are needed. At the moment the lithium ion type batteries offer technically good solutions for grid imbalance challenges and, as their costs decrease sufficiently, they can soon become an even more important part on the road to the carbon-neutral society.

References

Antic, R. et al., 2014. *Grid Inertia Supporting by Energy Storage Inverters,* Belgrade: Recent Advances in Intelligent Control, Modelling and Simulation.

Aslani, A. et al., 2013. Energy diversification in Finland: achievements and potential of renewable energy development. *International Journal of Sustainable Energy,* 10 January, 32(5), pp. 504-514.

Bertram, R., 2017. *Energy Post: Why Germany needs a European Energiewende.* [Online]
Available at: http://energypost.eu/14459-2/
[Accessed 2 May 2017].

Cheng, F. & Chen, J., 2012. Metal-air batteries: from oxygen reduction electrochemistry to cathode catalysts. *Chem. Soc. Rev.,* 41(6), pp. 2172-2192.

Costello, A. et al., 2009. Managing the health effects of climate change. *The Lancet,* 16 May, 373(9676), pp. 1693-1733.

Divya, K. & Østergaard, J., 2009. Battery energy storage technology for power systems—An overview. *Electric Power Systems Research,* 79(4), pp. 511 - 520.

DOE Global Energy Storage Database, 2017. *Projects and database results.* [Online]
Available at: http://www.energystorageexchange.org/projects
[Accessed 29 March 2017].

Dunn, B., Kamath, H. & Tarascon, J.-M., 2011. Electrical Energy Storage for the Grid: A Battery of Choices. *Science,* 18 November, 334(6058), pp. 928-935.

Electrek, 2017. *Tesla is now claiming 35% battery cost reduction at 'Gigafactory 1' – hinting at breakthrough cost below $125/kWh.* [Online]
Available at: https://electrek.co/2017/02/18/tesla-battery-cost-gigafactory-model-3/
[Accessed 14 April 2017].

Entso-e, 2017. *European Network of Transmission System Operators for Electricity: Regional groups.* [Online]
Available at: https://www.entsoe.eu/about-entso-e/system-operations/regional-groups/Pages/default.aspx
[Accessed 26 May 2017].

Fingrid, 2016a. *Power system.* [Online]
Available at: http://www.fingrid.fi/en/powersystem/Pages/default.aspx
[Accessed 4 November 2016].

Fingrid, 2016b. *Nordic power system and interconnections with other systems.* [Online]
Available at:
http://www.fingrid.fi/en/powersystem/general%20description/Nordic%20power%20system%20and%20interconnections%20with%20other%20systems/Pages/default.aspx
[Accessed 7 November 2016].

Fingrid, 2016c. *Power system management.* [Online]
Available at:
http://www.fingrid.fi/en/powersystem/Power%20system%20management/Pages/default.aspx
[Accessed 7 November 2016].

Fingrid, 2016d. *Responsibility for the power system and its operation.* [Online]
Available at:
http://www.fingrid.fi/en/powersystem/general%20description/Responsibility%20for%20power%20system/Pages/default.aspx
[Accessed 8 November 2016].

Fingrid, 2016e. *Power System in Finland.* [Online]
Available at:
http://www.fingrid.fi/en/powersystem/general%20description/Power%20System%20in%20Finland/Pages/default.aspx
[Accessed 8 November 2016].

Fingrid, 2016f. *Market places.* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/Demand-Side_Management/Market_places/Pages/default.aspx
[Accessed 9 November 2016].

Fingrid, 2016g. *Reserves.* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/reserves/Pages/default.aspx
[Accessed 9 November 2016].

Fingrid, 2016h. *Frequency control processes.* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/reserves/reservetypes/Pages/default.aspx
[Accessed 14 November 2016].

Fingrid, 2016i. *Balancing power market.* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/reserves/acquiring/market/Pages/default.aspx
[Accessed 15 November 2016].

Fingrid, 2016j. *Nopea häiriöreservi (in Engl. "Fast disturbance reserve").* [Online]
Available at:
http://www.fingrid.fi/fi/sahkomarkkinat/reservit/reservien_hankinta/Nopea_hairioreservi/Sivut/default.aspx
[Accessed 15 November 2016].

Fingrid, 2016k. *Frequency restoration reserves.* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/reserves/reservetypes/restoration/Pages/default.aspx
[Accessed 16 November 2016].

Fingrid, 2016l. *Automatic frequency regulating reserve (aFRR).* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/reserves/acquiring/automaticregulating/Pages/default.aspx
[Accessed 16 November 2016].

Fingrid, 2016m. *Toteutuneet tuntikaupat, ylössäätökapasiteetti (in Engl. "Realized hourly transactions, FRR-A capacity").* [Online]
Available at:
http://www.fingrid.fi/fi/sahkomarkkinat/taajuusohjatutreservit/automtaajuusfrra/Sivut/toteutuneet-tuntikaupat-ylossaatokapasiteetti.aspx
[Accessed 16 November 2016].

Fingrid, 2016n. *Liite 1: Automaattisen taajuudenhallintareservin sovellusohje (in Engl. "Appendix 1: Application instructions for automatic frequency restoration reserves").* [Online]
Available at:
http://www.fingrid.fi/fi/voimajarjestelma/voimajarjestelmaliitteet/Reservit/2016/Liite%201%20-%20Automaattisen%20taajuudenhallintareservin%20sovellusohje.pdf
[Accessed 6 February 2017].

Fingrid, 2016o. *Taajuuden vakautusreservit (in Engl. "Frequency containment reserves").* [Online]
Available at:
http://www.fingrid.fi/fi/sahkomarkkinat/reservit/reservilajit/Taajuuden_vakautusreservit/Sivut/default.aspx
[Accessed 17 November 2016].

Fingrid, 2016p. *Appendix 2: Application instruction for the maintenance of frequency controlled reserves, version 2016.* [Online]
Available at:
http://www.fingrid.fi/en/powersystem/Power%20system%20attachments/2016/Appendix%202%20-%20FCR%20application%20instruction%202016.pdf
[Accessed 18 November 2016].

Fingrid, 2016q. *Appendix 3: Rules and fees for the hourly market of frequency controlled reserves, version 2016,* Helsinki: Fingrid.

Fingrid, 2016r. *Frequency Containment Reserves (FCR).* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/reserves/acquiring/normaloperation/Pages/default.aspx
[Accessed 18 November 2016].

Fingrid, 2016s. *Frequency controlled normal operation reserve.* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/frequency-controlled-reserves/hourlytransactions/Pages/normaloperationreserve.aspx
[Accessed 1 December 2016].

Fingrid, 2017a. *Frequency measurement data.* [Online]
Available at:
http://www.fingrid.fi/en/powersystem/Power%20system%20management/Maintaining%20of%20balance%20between%20electricity%20consumption%20and%20production/Frequency%20measurement%20data/Pages/default.aspx
[Accessed 2 February 2017].

Fingrid, 2017b. *Liite 3: Taajuusohjattujen reservien tuntimarkkinoiden säännöt ja maksut, versio 2017 (in Engl. "Appendix 3: Rules and fees of FCR hourly markets, version 2017"),* Helsinki: Fingrid.

Fingrid, 2017c. *Vuosimarkkinat (in Engl. "Yearly markets").* [Online]
Available at:
http://www.fingrid.fi/fi/sahkomarkkinat/taajuusohjatutreservit/toteutuneettuntikaupat/vuosihinnat/Sivut/default.aspx
[Accessed 6 April 2017].

Fingrid, 2017d. *Frequency controlled disturbance reserve.* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/frequency-controlled-reserves/hourlytransactions/Pages/disturbancereserve.aspx
[Accessed 6 April 2017].

Fingrid, 2017e. *Frequency controlled normal operation reserve.* [Online]
Available at: http://www.fingrid.fi/en/electricity-market/frequency-controlled-reserves/hourlytransactions/Pages/normaloperationreserve.aspx
[Accessed 6 April 2017].

Fingrid, 2017f. *Imbalance power.* [Online]
Available at: http://www.fingrid.fi/EN/ELECTRICITY-MARKET/IMBALANCE-POWER/Pages/default.aspx
[Accessed 11 May 2017].

Fortum, 2014. *Several benefits for flexibility in the power market,* Espoo: Fortum Oy (slide show for internal use).

Fortum, 2016. *Press release: Fortum continues its virtual power plant experiment with the launch of the biggest Nordic electricity storage pilot project.* [Online]
Available at: https://www.fortum.com/en/mediaroom/Pages/fortum-continues-its-virtual-power-plant-experiment-with-the-launch-of-the-biggest-nordic-electricity-storage-pilot.aspx
[Accessed 4 May 2017].

Fortum, 2017a. *Hydropower.* [Online]
Available at: http://www.fortum.com/en/energy-production/hydropower/pages/default.aspx
[Accessed 13 April 2017].

Fortum, 2017b. *World's oldest and newest energy storage side by side: hydropower and batteries,* Espoo: Fortum ForEnergy blog.

Gallo, A., 2014. *A Refresher on Net Present Value.* [Online]
Available at: https://hbr.org/2014/11/a-refresher-on-net-present-value
[Accessed 10 April 2017].

Garcia, B. et al., 2004. Room temperature molten salts as lithium battery electrolyte. *Electrochimica Acta,* 49(26), pp. 4583 - 4588.

GlobalData, 2016. *Grid Connected Battery Energy Storage System – Market Size, Competitive Landscape, Key Country Analysis and Forecasts to 2020,* London: GlobalData UK Ltd.

Haisheng, C. et al., 2009. Progress in electrical energy storage system: A critical review. *Progress in Natural Science,* 10 March, 19(3), pp. 291 - 312.

Hartmann, P. et al., 2012. A rechargeable room-temperature sodium superoxide (NaO2) battery. *Nature Materials*, 3 December, Volume 12, pp. 228 - 232.

Hazza, A., Pletcher, D. & Wills, R., 2004. A novel flow battery: A lead acid battery based on an electrolyte with soluble lead(ii) Part I. Preliminary studies. *Phys. Chem. Chem. Phys.*, 9 March, 6(8), pp. 1773-1778.

Huttunen, R., 2017. *Government report on the National Energy and Climate Strategy for 2030,* Helsinki: Ministry of Economic Affairs .

Höök, M. & Tang, X., 2013. Depletion of fossil fuels and anthropogenic climate change—A review. *Energy Policy,* Volume 52, pp. 797 - 809.

IEA, 2016a. *Key world energy statistics,* Paris: International Energy Agency.

IEA, 2016b. *Key Electricity Trends,* Paris: International Energy Agency.

IEA, 2016c. *Key World Energy Trends,* Paris: International Energy Agency.

Intriere, A., 2016. *NiCd Batteries.* [Online]
Available at: https://angelinaintriere.wordpress.com/2016/03/31/nicd-batteries/
[Accessed 21 April 2017].

ITICA, 2017. *Part 1: How Lead-Acid Batteries Work.* [Online]
Available at: http://www.itacanet.org/a-guide-to-lead-acid-battries/part-1-how-lead-acid-batteries-work/
[Accessed 6 Mars 2017].

Kervinen, T., 2010. *A linear programming approach to estimate hydropower supply in the Nordic electricity market,* Espoo: CiteSeerX.

Knap, V. et al., 2014. *Grid inertial response with Lithium-ion battery energy storage systems,* New York City: 2014 IEEE 23rd International Symposium on Industrial Electronics.

Lawder, M. T. et al., 2014. Battery Energy Storage System (BESS) and Battery Management System (BMS) for Grid-Scale Applications. *Proceedings of the IEEE,* 102(6), pp. 1014-1030.

McKinsey & Company, 2017. *Electrifying insights: How automakers can drive electrified vehicle sales and profitability,* San Francisco: Scribd Inc.

NGK Insulators, 2017. *Principle of NAS Battery.* [Online]
Available at: https://www.ngk.co.jp/nas/specs/
[Accessed 7 March 2017].

Nord Pool, 2016a. *Day-ahead market.* [Online]
Available at: http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/
[Accessed 10 November 2016].

Nord Pool, 2016b. *Price formation.* [Online]
Available at: http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/Price-formation/
[Accessed 10 November 2016].

Nord Pool, 2016c. *Intraday market.* [Online]
Available at: http://www.nordpoolspot.com/How-does-it-work/Intraday-market/
[Accessed 11 November 2016].

Nord Pool, 2017. *Elspot prices.* [Online]
Available at: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/ALL1/Yearly/?view=table
[Accessed 5 April 2017].

Nordic Folkecenter for Renewable Energy, 2009. *Flow battery.* [Online]
Available at: http://www.folkecenter.net/gb/rd/transport/fuels-and-supply/energy_storage/flow_battery/
[Accessed 8 March 2017].

Nykvist, B. & Måns, N., 2015. Rapidly falling costs of battery packs for electric vehicles. *Nature Clim. Change,* 23 March, 5(4), pp. 329 - 332.

Partanen, J., 2016. *Sähkön hinta (in Eng. "Electricity price"),* Lappeenranta: University of Technology.

Partanen, J. et al., 2014. *Sähkömarkkinat - opetusmoniste (in Engl. "Electricity markets - educational material"),* Lappeenranta: University of Technology.

Pöyry Group, 2016. *EU:n 2030 ilmasto- ja energiapolitiikan linjausten toteutusvaihtoehdot ja Suomen omien energia- ja ilmastotavoitteiden toteuttaminen,* (in Engl. "The implementation options from the EU's 2030 climate and energy policy guidelines and implementation of Finland's own energy and climate goals"). Helsinki: Valtioneuvoston selvitys- ja tutkimustoiminta.

Qian, H., Zhang, J., Lai, J. S. & Yu, W., 2011. A high-efficiency grid-tie battery energy storage system. *IEEE Transactions on Power Electronics,* March, 26(3), pp. 886-896.

Saft, 2014a. *Technical sheet: Lithium-ion battery systems.* [Online]
Available at:
http://www.saftbatteries.com/force_download/li_ion_battery_system__TechnicalSheet_en_0514_Protected.pdf
[Accessed 28 February 2017].

Saft, 2014b. *Technical sheet: Lithium-ion battery life.* [Online]
Available at:
http://www.saftbatteries.com/force_download/li_ion_battery_life__TechnicalSheet_en_0514_Protected.pdf
[Accessed 28 February 2017].

Saft, 2016. *Product brochure: Intensium Max.* [Online]
Available at:
http://www.saftbatteries.com/force_download/IntensiumMax_ProductBrochure_en_1116_Protected.pdf
[Accessed 31 January 2017].

Schramek, P., 2016. *Storage Markets.* [Online]
Available at: http://www.storage-markets.com/Frequency-Control-Market
[Accessed 2 May 2017].

Seppänen, R. et al., 2016. *MAOL-taulukot.* Helsinki: Otava.

Soloveichik, G. L., 2011. Battery Technologies for Large-Scale Stationary Energy Storage. *Annual Review of Chemical and Biomolecular Engineering,* 2(1), pp. 503-527.

Statistics Finland, 2016. *Uusiutuvilla energialähteillä tuotetun sähkön määrä ennätystasolla (in Engl. "Volume of electricity produced with renewable energy sources at record level"),* Helsinki: Tilastokeskus (in Engl. "Statistics Finland").

Steel, W., 2017. *Energy Storage Market Outlook 2017: State of Play.* [Online]
Available at: http://www.renewableenergyworld.com/articles/print/volume-20/issue-1/features/storage/energy-storage-market-outlook-2017-state-of-play.html
[Accessed 2 May 2017].

T&T, 2016. Supergraafi: Akkukisa alkoi suomessa (in Engl. "The battery race started in Finland"). *Tekniikka & Talous*, 2 December, Issue 40, pp. 10-11.

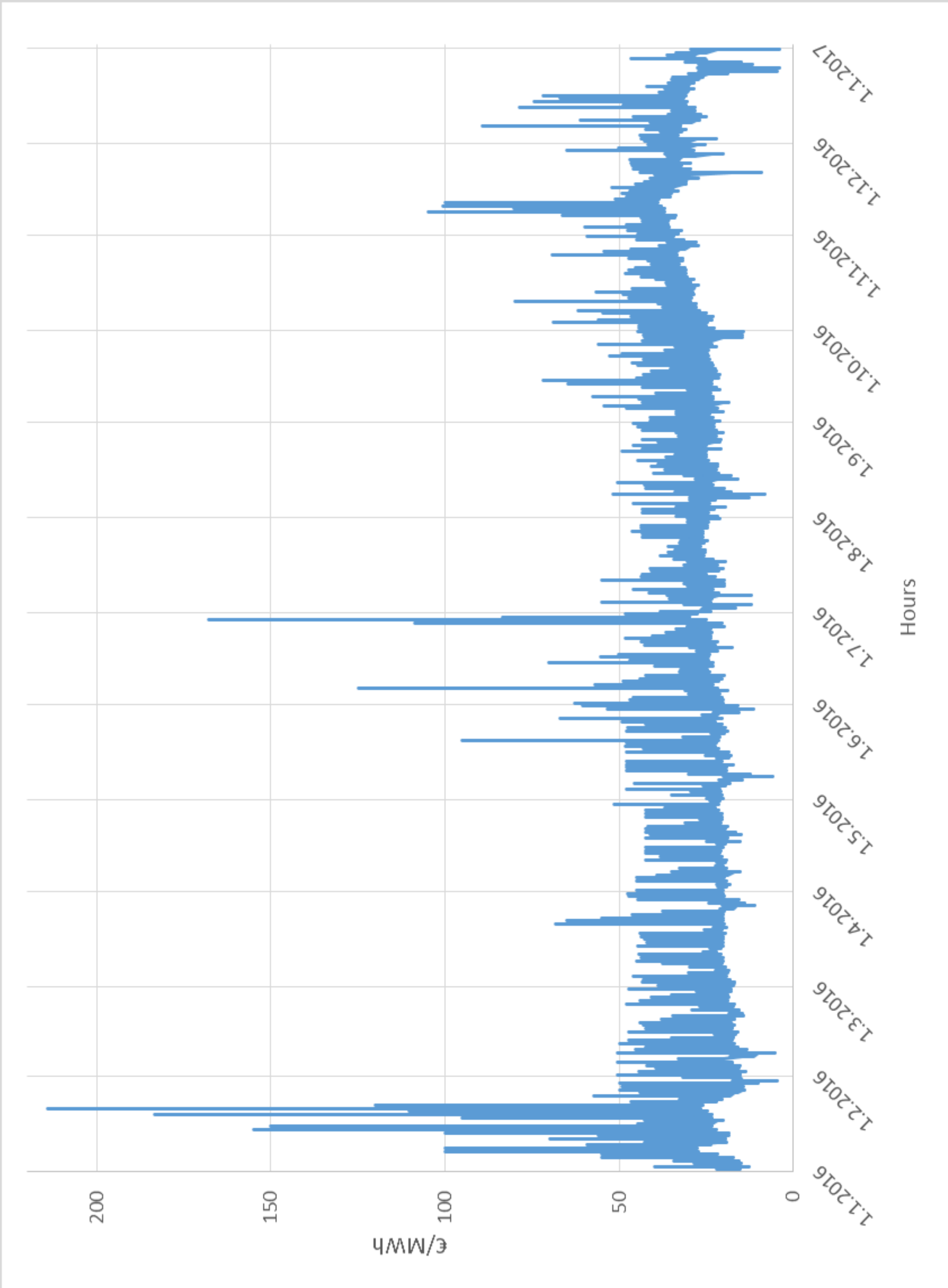
Tielens, P. & Van Hertem, D., 2012. *Grid Inertia and Frequency Control in Power Systems with High Penetration of Renewables,* Katholieke Universiteit Leuven: Young Researchers Symposium in Electrical Power Engineering edition:6.

Zhaoyin, W. et al., 2008. Research on sodium sulfur battery for energy storage. *Solid State Ionics,* 179(27–32), pp. 1697 - 1701.

List of appendices

Appendix 1. Elspot hourly prices in Finland

Elspot prices from the day-ahead market are portrayed in the chart below. Data points are represented as hourly prices (€/MWh) in Finland throughout the year 2016. Data source: (Nord Pool, 2017).



Appendix 2. Battery technology comparisons

The battery energy storage technology comparisons are represented on the table below. Data source: (Divya & Østergaard, 2009).

Battery type	Comments
Lead acid (flooded type)	η=72–78 %, cost [d]50–150, life span 1000–2000 cycles at 70 % depth of discharge, operating temperature −5 to 40 °C[a], 25 Wh/kg, self-discharge 2–5%/month, frequent maintenance to replace water lost in operation, heavy
Nickel Cadmium (NiCd)	η=72–78 %, cost [d]200–600, life span 3000 cycles at 100 % depth of discharge, operating temperature −40 to 50 °C, 45–80 Wh/kg, self-discharge 5–20 %/month, high discharge rate, negligible maintenance, NiCd cells are poisonous and heavy
Sodium Sulphur (NaS)	η=89 % (at 325 °C), life span 2500 cycles at 100 % depth of discharge, operating temperature 325 °C, 100 Wh/kg, no self-discharge, due to high operating temperature it has to be heated in stand-by mode and this reduces its overall η, have pulse power capability of over 6 times their rating for 30 s
Lithium ion	η≈100 %, cost [d]700–1000, life span 3000 cycles at 80 % depth of discharge, operating temperature −30 to 60 °C, 90–190 Wh/kg, self-discharge 1 %/month, high cost due to special packaging and internal over charge protection
Metal air	η=50 %, cost [d]50–200, life span few 100 cycles, operating temperature −20 to 50 °C, 450–650 Wh/kg, negligible self-discharge, recharging is very difficult and inefficient, compact
Vanadium redox (VRB)	η=85%, cost [d]360–1000, life span 10 000 cycles at 75 % depth of discharge, operating temperature 0–40 °C, 30–50 Wh/kg, negligible self-discharge
Regenerative fuel cell (PSB)	η=75 %, cost [d]360–1000, operating temperature 0–40 °C, negligible self-discharge
Zinc Bromine	η=75 %, cost [d]360–1000, operating temperature 0–40 °C, 70 Wh/kg, negligible self-discharge, low power, bulky, hazardous components

a	*Operating at higher temperature will reduce the life and operating at lower temperature will reduce the efficiency.*
b	*At Milwauke, Wisconsin.*
c	*Provides 10 MVar even when the battery is not discharging.*
d	*Capital cost in Euro/kWh.*

Appendix 3. Simulation functions for Batcave model

The simulation functions of Batcave model are represented below. The pictures are taken from the complete Batcave model excel sheet that includes both simulation functions and summary functions. In order for the content of formulas to be shown clearly the functions are arranged in order for distinct sections.

For Columns A and B the frequency measurement data from the year 2016 was implemented. In the Column A the time series of data points are running for every second for every row. In the Column B the frequency measurement points are listed for every second. Generally it can stated that the first function row of Row 2 collects the day's starting values for the simulations. Next, the Row 3 includes the actual simulation functions that are then duplicated for every second that there is frequency data available.

	A	B	C
1			**f_conditional (Hz)**
2			=IF(B2=""; 50; IF(B2<49,9; 49,9; IF(B2>50,1; 50,1; B2)))
3			=IF(B3=""; 50; IF(B3<49,9; 49,9; IF(B3>50,1; 50,1; B3)))
4			

	D
1	**P (MW)**
2	=IF(AND(C2>=49,9;C2<49,95);40*C2-1998;IF(AND(C2>=49,95;C2<=50,05);0;40*C2-2002))
3	=IF(AND(C3>=49,9;C3<49,95);40*C3-1998;IF(AND(C3>=49,95;C3<=50,05);0;40*C3-2002))
4	

	E	F
1	**E_in (MWh)**	**E_out (MWh)**
2	=IF(D2>0; D2*(1/(3600));)	=IF(D2<=0; D2*(1/(3600));)
3	=IF(I2>=$V$1; 0; IF(D3>0; D3*(1/(3600));))	=IF(I2<=$W$1; 0; IF(D3<=0; D3*(1/(3600));))
4		

	G	H
1	**E_in_not (MWh)**	**E_out_not (MWh)**
2	=IF(I2=$V$1; IF(D2>0; D2*(1/(3600)); 0); 0)	=IF(I2=$W$1; IF(D2<=0; D2*(1/(3600)); 0); 0)
3	=IF(I3=$V$1; IF(D3>0; D3*(1/(3600)); 0); 0)	=IF(I3=$W$1; IF(D3<=0; D3*(1/(3600)); 0); 0)
4		

	I	J
1	E_tot (MWh)	SOC (%)
2	`=Y1+E2+F2`	`=I2/1`
3	`=IF(C3="";I2;IF(I2>=$V$1;$V$1+F3;IF(I2<=$W$1;$W$1+E3;I2+E3+F3)))`	`=I3/1`
4		

	K	L
1	E_hypot. (MWh)	E_extra (MWh)
2	`=PERSONAL.XLSB!PrevSheet($AT$1)+E2+F2`	`=PERSONAL.XLSB!PrevSheet($AV$1)+G2+H2`
3	`=IF(C3="";K2;K2+E3+F3+G3+H3)`	`=IF(C3="";L2;L2+G3+H3)`
4		

The limit of battery's energy capacity has an important influence on the simulation functions. Batcave battery has an energy capacity of 1 MWh and with 10 % buffers the used boundary values and excel cell positions are listed below. The size values could be changed if there is need to conduct simulations with different battery specifications.

Abbreviation	Cell	Definition	Value
E_tot_max	V1	Maximal energy value that the battery can have in full state.	0,9 MWh
E_tot_min	W1	Minimal energy value that the battery can have in empty state.	0,1 MWh

The *PrevSheet*-formula is displayed in Appendix 5.

Appendix 4. Summary functions of Batcave model

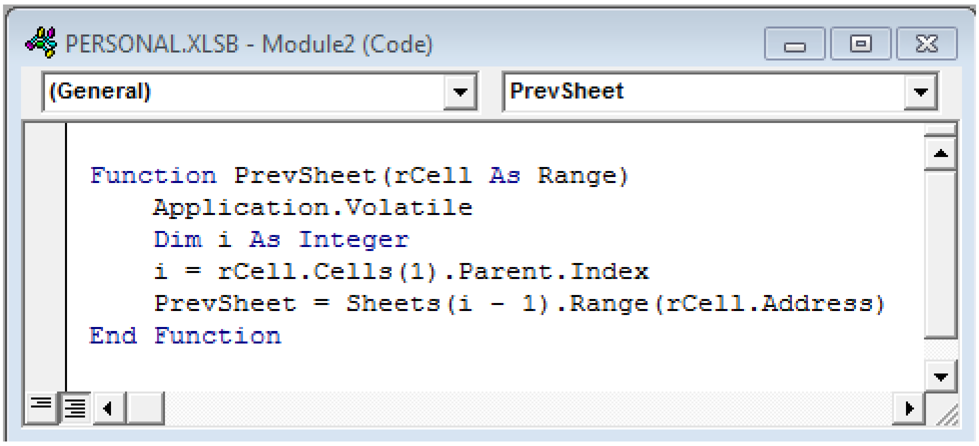
The summary functions of Batcave model are represented below. The formulas are taken from the complete Batcave model excel sheet that includes both simulation functions and summary functions. In order for the content of formulas to be shown clearly the functions are listed in order with their excel sheet cell positions and used formulas.

Abbreviation	Unit	Cell	Summary function formula
E_in_sum	MWh	N1	=SUM($E:$E)
E_out_sum	MWh	O1	=SUM($F:$F)
Active hours	h	R1	=COUNT($C:$C)/3600
E_tot_start	MWh	Y1	=PERSONAL.XLSB!PrevSheet($AR$1)
Cycle count	-	AA1	=$N$1*0,5-$O$1*0,5
E_in_not_sum	MWh	AC1	=SUM($G:$G)
E_out_not_sum	MWh	AD1	=SUM($H:$H)
First time full	h	AF1	{=(MATCH($V$1;$I:$I; 0)-MATCH(TRUE; ISNUMBER($I:$I); 0))/3600}
First time empty	h	AG1	{=(MATCH($W$1;$I:$I; 0)-MATCH(TRUE; ISNUMBER($I:$I); 0))/3600}
Idle time full	h	AI1	=(COUNTIF($G:$G;">0"))/3600
Idle time empty	h	AJ1	=(COUNTIF($H:$H;"<0"))/3600
E_hypot. MAX	MWh	AL1	=MAX($K:$K)
E_hypot. MIN	MWh	AM1	=MIN($K:$K)
E_extra MAX	MWh	AO1	=MAX($L:$L)
E_extra MIN	MWh	AP1	=MIN($L:$L)
Last E_tot	MWh	AR1	=LOOKUP(2;1/($I:$I<>"");$I:$I)
Last E_hypot.	MWh	AT1	=LOOKUP(2;1/($K:$K<>"");$K:$K)
Last E_extra	MWh	AV1	=LOOKUP(2;1/($L:$L<>"");$L:$L)

The *PrevSheet*-formula is displayed in Appendix 5.

Appendix 5. VBA-code for *PrevSheet*-formula

As Microsoft Excel program didn't have a standard formula for linking automatically to previous sheet it had to be coded to the VBA program. The *PrevSheet*-formula in question is displayed below as it is used in the simulations and coded in Microsoft Visual Basic for Applications software.




```
Function PrevSheet(rCell As Range)
    Application.Volatile
    Dim i As Integer
    i = rCell.Cells(1).Parent.Index
    PrevSheet = Sheets(i - 1).Range(rCell.Address)
End Function
```